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UNIVERSITY OF CALGARY

GEOMATICS ENGINEERING

Final Report on

TACTICAL INDOOR POSITIONING SYSTEM (TIPS) OPTIONS STUDY

for

Department of National Defence
Defence Research Establishment Ottawa
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EXECUTIVE SUMMARY

The Defence Research Establishment Ottawa (DREO) has a requirement to explore the possible technologies that could be used to implement a Tactical Indoor Positioning System (TIPS) that will provide a nominal 3D (three dimensional) accuracy of 1 metre, for the geo-location of personnel inside an arbitrary structure. Since people to be geo-located are collaborating and are willing to carry special equipment, it must be light, portable, of small size, very rugged, highly reliable and with low power consumption.

This study identifies technologies that can be considered in a future R&D project to implement a proof-of-concept technology demonstration that will attempt to achieve 1 metre 3D positioning accuracy under the widest possible range of operating environments. Existing and emerging RF and self-contained technologies are reviewed for indoor location and to propose potential systems that could be considered for evaluation.

A basic technology survey was done to identify possible technological solutions that will meet the desirable or essential system specifications. A range of technologies were considered including low signal level GPS, special purpose beacon transmitters and receivers using Time of Arrival, Time Difference of Arrival or other signal processing techniques, inertial technology, Ultra Wideband (UWB) RF techniques, and other multi-sensor integrated combinations. These technologies were assessed according to features such as their characteristics, operating environment, error sources, accuracy performance, limitations, and availability (including vendors).

The anticipated performance of potential systems that incorporate one or more of the basic technologies was assessed according to the system requirements for four hypothetical operating environments. These environments ranged from a three-story wooden building of construction consistent with a large private residence to a large reinforced concrete building of construction consistent with a military headquarters. The potential systems were then rated as to whether they met the essential requirements, desired requirements, neither of the requirements, or if the performance with respect to the requirements was unknown at this time.

Based on the analysis of potential systems, two technologies appear promising: (1) combined ground-based RF and INS technologies, supplemented with a short-range differential barometry system for the height component, and (2) emerging Ultra Wideband systems. Ultra Wideband systems are currently not available for testing and there is still uncertainty as to the performance of an RF-based system indoors. Therefore, a proposal to investigate various technical aspects of the penetration and accuracy performance of RF signals through different types of buildings, and the system design considerations for such a system, is included as a first step for further research and testing.

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1. OBJECTIVE AND TASKS

The Defence Research Establishment Ottawa (DREO) has a requirement to explore the possible technologies that could be used to implement a Tactical Indoor Positioning System (TIPS) that will provide a nominal 3D (three dimensional) accuracy of 1 metre, for the geo-location of personnel inside an arbitrary structure. The probability level associated with the above accuracy is given in Table 1. The people to be geo-located are collaborating and are willing to carry special equipment. This requires that the equipment carried be light, portable, of small size, very rugged, highly reliable and with low power consumption. It is intended that the technologies identified in this options study will be used in a future R&D project to implement a proof-of-concept technology demonstration that will attempt to achieve 1 metre 3D positioning accuracy under the widest possible range of operating environments.

The objective of the work proposed herein is to review existing and emerging RF and self-contained technologies for indoor location and to propose potential systems that could be considered for evaluation. This study consists of the following tasks:

1. Technology Survey: Identification of possible technological solutions that will meet the desirable or essential system specifications summarized in Table 1, which may include (but is not limited to):
   - (i) Commercially available indoor geo-location systems
   - (ii) Low signal level GPS
   - (iii) Loran C
   - (iv) Special purpose beacon transmitters and receivers using Time of Arrival, Time Difference of Arrival or other signal processing techniques
   - (v) Innovative signal processing techniques, such as double or triple differencing
   - (vi) Inertial technology
   - (vii) Micro-electromechanical sensors (MEMS)
   - (viii) Nav Aids (e.g. Pedometers, Magnetic compasses, etc.)
   - (ix) Imaging Technology
   - (x) Infrared or acoustic tracking
   - (xi) Ultra Wideband (UWB) RF techniques
   - (xii) Other multi-sensor integrated combinations

2. Anticipated Performance of Potential Systems: Each of the identified possible solutions are to be inter-compared with respect to how well they meet the system requirements given in Table 1 in each of the following four hypothetical operating environments:
   - (i) A three-story wooden building of construction consistent with a large private residence;
   - (ii) A twenty-story steel and glass building of construction consistent with an urban office tower;
   - (iii) An underground earthen, concrete and steel structure of construction consistent with a subway tunnel;
   - (iv) A large reinforced concrete building of construction consistent with a military headquarters.

3. Prototype Recommendation: Based on the analysis of the previous tasks, one or possibly two technologies for further research and testing are to be recommended, along with justification and any acknowledged limitations.

4. Preliminary Design. A preliminary design of a Technology Demonstrator based on the recommended solution(s), along with suitable test and evaluation procedures to be explored further in possible future studies, is to be proposed.

5. Cost Estimates. Cost estimates to carry out the detailed design, procurement, construction, testing and evaluation of the Technology Demonstrator proposed in Task 4 are to be provided.

Table 1: Summary of DND TIPS Requirements

	Requirement	Essential	Desirable
Performance	*Accuracy, Horizontal*	1 metre, CEP	1 metre, 2drms
	Accuracy, Vertical	1 metre, PE	1 metre, 2σ
	Operating Environment	Wooden low-rise, Office tower	Subway Tunnel, Military HQ
	Velocity Requirement	5 m/s	10 m/s
	Update Rate	1 Hz	10 Hz
	Operating Time	30 minutes	2 hours
	Set-up/Calibration Time	30 minutes	None
	Emission Control	No restrictions	Passive
Physical	*Weight*	5 kg	1 kg
	Volume	2500 cm^3	250 cm^3
	Cost	No limit at this time	$5000 US per unit

An unstated requirement is that, if RF methods are used, no fixed transmitters or receivers can be assumed to be pre-installed or installed inside buildings. Typically, the only transmitters or receivers inside buildings would be the ones carried by the users. All other transmitters and receivers must be rapidly deployable and capable of operating outside the line of sight of the mobile users, usually from outside the structure. The use of RF methods thus implies transmission from outdoors to indoors or vice-versa, as opposed to the outdoor-outdoor or indoor-indoor transmission cases, these being more straightforward.

2. BASIC TECHNOLOGY SURVEY

The following sections document core technologies to be considered for indoor positioning.

2.1 Spread Spectrum Terrestrial Positioning Systems

TOA (Time Of Arrival) and TDOA (Time Difference Of Arrival) estimation by correlating a received signal with a replica of the signal is a common technique used for position estimation. The accuracy of the TOA estimate derived from correlation, and hence the position estimate accuracy, is largely a function of the signal bandwidth. Spread spectrum signals are, therefore, ideal for this in that they have a relatively large bandwidth.

Two general types of spread spectrum signals exist. The first is direct sequence (DS) spread spectrum in which the signal to be transmitted is modulated by a pseudo-random code with a high bit rate. The resultant signal is spread across a large bandwidth and falls to the noise floor making it very difficult to detect and demodulate by any receiver other than the intended one (Proakis, 1989). A number of such signals may coexist in the same spectrum if they are modulated with codes that are nearly orthogonal. At the receiver, the received signal is again mixed with the same code that despreads it yielding the original signal. Frequency-hopped spread spectrum signals are created by dividing the available bandwidth into a number of frequency slots. At any one time the signal to be transmitted occupies a particular frequency slot. The order in which the signal hops from one frequency slot to another is dictated by a pseudo-random code. Direct sequence spread spectrum signals are generally used for position estimation.

Terrestrial-based spread spectrum positioning systems operate in much the same manner as GPS, which also uses spread spectrum signals. Most often, however, terrestrial-based systems are inverted forms of GPS. In a terrestrial-based system, a mobile transmitter of unknown position transmits to a number of fixed receivers of known position rather than a number of satellites of known position transmitting signals to a receiver that estimates its own position. Terrestrial systems have a distinct advantage over GPS. Because the transmitter and receiver are so much closer in a terrestrial system than in GPS, the received signal levels can be made significantly higher. This makes indoor positioning far easier for a terrestrial-based system. Spread spectrum signals do suffer from the near-far problem, however, and this is particularly true for terrestrial systems. Depending on how close to orthogonal the codes used by different transmitters are, a transmitter close to a receiver may swamp out the signal of a transmitter that is far away. In terms of estimation accuracy, multipath and the absence of line of sight propagation continue to be the limiting factors.

Both commercial and military spread spectrum systems have been developed. Peterson et. al. (1999, 1998) developed, implemented and tested a spread spectrum, indoor geo-location system for the U.S. Defense Advanced Research Projects Agency (DARPA). The system was specifically developed to track the location of personnel inside of buildings. It makes use of a small spread spectrum transmitter carried on the person. A network of receivers of known position in an appropriate geometry for 3D locations is deployed outside of the building of interest. These receivers are time synchronized via a fixed reference transmitter also outside the

building and also of known position. A 3D position update is generated every second. During a field test conducted in a wooden two-story building, 90% of the position estimates were within 2.86 m of ground truth. Accurate estimation of which floor the soldier was on was obtained by a sliding average of 10 height measurements. Although leading edge detection of the correlation envelope was employed in the TOA estimation process, multipath continued to be the major error source.

Another positioning system based on the TOA of spread spectrum signals transmitted by a mobile transmitter has been developed by the Telecommunications and Industrial Physics branch of CSIRO (Commonwealth Scientific & Industrial Research Organisation) in Australia (see http://www.tip.csiro.au/). The system has two modes of operation. Either TOA and AOA (Angle Of Arrival) are estimated at one fixed receiver site, or, TOA is estimated at four fixed receiver sites. It is unclear how often a position fix is delivered, whether the system delivers a 2D or 3D solution, and how well the system works indoors. For the single receiver mode of operation, accuracies better than 5 m over distances of 1 km in high multipath urban centres have been claimed. In multiple receiver mode, nominal accuracies of 40 mm have been achieved in open fields with line-of-sight propagation.

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Peterson, B., C. Kmiecik, R. Hartnett, P. Thompson, J. Mendoza, (1998), *Spread Spectrum Indoor Geolocation*, Navigation: Journal of the Institute of Navigation, Vol. 45, No. 2, Summer.

CISRO Telecommunications and Industrial Physics Website. URL: http://www.tip.csiro.au/

2.1.1 Example System – Peterson/U.S. Coast Guard

Table 2: Technology Profile for US Coast Guard Spread Spectrum System

Technology Characteristics	Principle of Operation	TDOA – mobile transmitter and multiple fixed receivers of known position.
	Sensors	DS Spread Spectrum TOA receivers
	Observables	TOA
	Navigation Information Provided	3D fix on floor plan overlay
	Other Characteristics	Receiver synchronization via a fixed reference transmitter of known position. (GPS 1PPS used for this purpose) Multipath mitigation via leading edge detection of correlation envelope. 1s position fix update interval. Carrier frequency 256 MHz Chip rate: 51.2 MHz Signal Bandwidth 102.4 MHz PN sequence length 4096 chips (80 μs) Sampling frequency 204.8 MHz
Operational Environment	Mobile indoors (2 story wood-frame house) with receivers and reference transmitter immediately outdoors.	
System Error Sources	Multipath Geometry of transmitters and receivers	
System Error Characteristics	Position errors appear normally distributed. Multipath bias System software constrains the transmitter within the walls of the building. Outside fixes snapped to closest point 0.5 m inside the building.	
A Priori Information	Precise location of receivers and reference transmitter. Synchronization of receiver clocks to reference transmitter clock. Floor plan of building.	
Detectability	Receivers are physically visible. Signal "invisibility" and resistance to jamming inherent in spread spectrum communications.	
Limitations	Set-up time required for positioning receivers and reference transmitter. Receivers and reference transmitters require clear view of sky. Unclear whether transmitted power (20 dBm max) sufficient for penetration of other building types and for long distances between mobile transmitter and receivers. Vertical accuracy is highly sensitive to transmitter/receiver geometry in 3D.	
Advantages	Spread spectrum limits jamming and hostile signal detection. Multiple mobiles should be possible given orthogonal codes.	
Vendors	None	

Example Systems	US Coast Guard Academy System funded by DARPA
Accuracy Performance (Stand-alone mode)	90% of fixes within 2.86 m of ground truth. Maximum error of 10 m. Accurate vertical resolution to correct floor using 10 fix sliding window average of heights.

2.1.2 Example System - TOA and/or AOA – CISRO System

Table 3: Technology Profile for CISRO Spread Spectrum System

Technology Characteristics	Principle of Operation	Mobile transmitter of spread spectrum signal. 1) TOA and AOA estimated at one fixed base station of known position. 2) TOA (and AOA?) estimated at four fixed base stations of known position.
	Sensors	TOA and AOA estimators.
	Observables	TOA, AOA
	Navigation Information Provided	2D position
	Other Characteristics	Spread spectrum transmission in ISM band.
Operational Environment	Primarily outdoor in all environments. Indoor ability unknown.	
System Error Sources	Multipath Geometry	
System Error Characteristics		
A Priori Information	Precise positions of base stations.	
Detectability	Signal "invisibility" and resistance to jamming inherent in spread spectrum communications.	
Limitations	Range - 1 km for system 1) (one base station) - 2 km by 2km area for system 2) (four base stations)	
Advantages	Spread spectrum limits jamming and hostile signal detection. Multiple mobiles should be possible given orthogonal codes.	
Vendors	CSIRO Australia	
Example Systems		
Accuracy Performance (Stand-alone mode)	1) better than 5 m in high multipath urban centres 2) nominally 40 mm (open field with good line-of-sight)	

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2.2 Ultra Wideband Positioning

Ultra wideband (UWB) technology is also known as impulse, carrier free, baseband, or non-sinusoidal technology. UWB signals are commonly defined as signals with a bandwidth of at least 25% of the centre frequency of the signal. They are produced by generating and transmitting short pulses of RF energy (on the order of nanoseconds and less). These pulses may be just a few cycles of the RF carrier.

UWB signals share many of the properties of spread spectrum signals. Their wide bandwidth makes them difficult to detect, tolerant of other RF interference and relatively resistant to multipath. Both spread spectrum and UWB signals may be used for communication and positioning. According to Multispectral Solutions Inc., UWB positioning systems do, however, enjoy some advantages over spread spectrum systems (see Multispectral Solutions Inc. Website http://www.multispectral.com. The primary advantage cited by Multispectral Solutions Inc. is significantly lower implementation complexity and cost. Another may be better multipath rejection capability. Both UWB and spread spectrum signals are of large bandwidth and, therefore, yield a very fine measurement resolution and excellent multipath mitigation. UWB receivers that employ leading edge detection, however, are practically able to distinguish between arrivals spaced by the signal length of only a few nanoseconds. Spread spectrum signals must employ very high chipping rates to achieve the same resolution and the codes used must be sufficiently orthogonal to their time shifted replicas to achieve multipath immunity.

Positioning with UWB technology is accomplished by measuring the TOA or TDOA of UWB signals. Multispectral Solutions Inc., one developer of an UWB positioning system uses tunnel diodes to accomplish leading edge detection of the UWB pulses (Fontana, 2000). The mobile transceiver transmits a sequence of these pulses that is received by a number of beacons of known position. The beacons transmit these signals back to the mobile transceiver after a known turn around delay. The mobile transceiver estimates the TOA of these return transmissions and thereby calculates the return distance to each of the beacons. Note that this active, two-way system is self-synchronizing and, therefore, does not require external time synchronization.

The Multispectral system has demonstrated both indoor and outdoor positioning with RMS range errors from 15 cm to 90 cm and measurement standard deviations on the order of 6 cm to 15 cm. Positioning precision will, of course, depend on the geometry of the beacons with respect to the mobile transmitter as quantified by the appropriate DOP (Dilution Of Precision) values. In the accompanying table, horizontal accuracy is given as the product of the appropriate range error and the HDOP (Horizontal DOP) and vertical accuracy is given as the product of the appropriate range error and the VDOP (Vertical DOP). Time Domain, another company offering an UWB positioning system, claims "an accurate positioning range of less than one inch" (see Time Domain website).

Range accuracy is a function of the material between the transmitter and receiver. None of the companies reporting on their systems discuss accuracy performance versus the indoor propagation medium. When high levels of accuracy are reported, it is suspected that the transmitter and receiver are in a line of sight situation or that the walls between them are made of material that offers little resistant to RF signals.

References:

Fontana, R.J., (2000), *Experimental Results from an Ultra Wideband Precision Geolocation System*, EuroEM 2000, Edinburgh, Scotland, 30 May 2000, to be published in Ultra-Wideband, Short-Pulse Electromagnetics, Kluwer Academic/Plenum Publishers.

Multispectral Solutions Inc. Website. URL: http://www.multispectral.com

Aether Wire and Location Inc. Website. URL: http://www.aetherwire.com

Time Domain Website. URL: http://www.time-domain.com

Table 4: Technology Profile for Ultra Wideband

Technology Characteristics	Principle of Operation	Two-way TOA – mobile transmitter (ranger) and multiple fixed transceivers (beacons) of known position.
	Sensors	Ranger and beacons each consist of ultra wideband transmitter, low noise amplifier, tunnel diode detector and synchronization circuitry.
	Observables	Ranges
	Navigation Information Provided	2D or 3D position fix depending on geometry
	Other Characteristics	2.5 ns burst waveform Bandwidth is 400 MHz. Centre frequency of 1.5 GHz. Tunnel diode used for leading edge pulse detection. Line of sight range is 2 km. Indoor range is approximately 100 m.
Operational Environment	Outdoor/indoor and indoor/indoor.	
System Error Sources	Multipath Low SNR due to attenuation	
System Error Characteristics	For indoor beacon placements, areas of good geometry may be limited.	
A Priori Information	Precise positions of beacons.	
Detectability	Low probability of detection due to large bandwidth and low energy density. Location calculated at mobile and needs to be transmitted back to interested parties.	
Limitations	Two-way active systems are restricted to a certain number of systems – depends on hardware.	
Advantages	High immunity to multipath. High measurement resolution. Beacons are untethered (no cables). Two-way self-synchronizing time system.	
Vendors	Multispectral Solutions Inc., Time Domain, Aether Wire and Location	
Example Systems	Technology characteristics above are for the Multispectral Solutions Inc. UWB positioning system.	
Accuracy Performance (Stand-alone mode)	Outdoor - measurement standard deviation of 6 cm - RMS range error < 15 cm Indoor - typical measurement standard deviation is 15 cm - RMS range error from 15 cm to 90 cm	

2.3 Mobile Telephone Positioning

A significant application of personal positioning is E-911 services for wireless telephones. The FCC has mandated that wireless service providers implement methods of automatically determining the position of wireless telephones when used to call 911 (http://www.fcc.gov/e911/factsheet_requirements_012001.txt).

Two general approaches exist to accomplish automatic location identification (ALI) for wireless telephones. One is to implement technology in the mobile handset that allows the handset to determine its position or a server to determine the handset's position based on information provided by the handset. Embedding a GPS receiver in the handset is the most common approach. Since wireless handsets work indoors, a GPS receiver in the handset must also be able to acquire GPS satellite signals indoors. This requires special signal processing techniques and strategies. These technologies are covered under high sensitivity and network-aided GPS elsewhere in this report.

The second approach to wireless telephone positioning is network-based – the technology to estimate the handset position resides primarily in the network. Although some handset methods based on GPS also rely on the network (i.e. network-aided GPS), they are distinguished from network-based techniques due to the location of the sensors. For a GPS-handset technique the sensors making the observation reside in the handset. For a network-based approach the sensors making the observations reside in the network. The exception to this is the technique of enhanced observed time difference (E-OTD) in which the observations are made by the handset. The observations made in E-OTD are not GPS-based, however, and as a result the technique has more in common with network-based methods. Therefore, E-OTD is herein classified as a network-based approach.

In network-based methods, either or both the AOA or TOA of signals transmitted between the wireless handset and the network, are estimated at a number of sites. Position may then be estimated by triangulation in the case of AOA, trilateration in the case of TOA, or a combination of the two. Strength of arrival (SOA) is another possible observation but is generally not very accurate for wireless telephone signals. Location by SOA is treated elsewhere in this report and is also known as location by received signal strength.

In some systems, receivers located at fixed locations of precisely known position estimate the TOA or AOA of signals transmitted by the handset. For TOA estimation, these receivers must be time synchronized and this is generally achieved through the use of GPS. The TOA and/or AOA estimates are communicated to a central processing site that estimates the position of the wireless telephone. Companies such as Cell-Loc Inc., TruePosition, and Grayson Wireless have developed such systems. For an overview of the Cell-Loc system see Klukas et. al. (1998) and Fattouche et. al. (1999). A description of the TruePosition system may be found in Stilp et. al. (1994).

The advantages of such systems include:

- The environment in which a mobile handset may be positioned is generally anywhere that the handset can make and receive calls. This includes indoor areas.

- Mobile handsets generally do not require any modifications. As a result, such systems are able to position legacy handsets.

- A special transmitter for positioning purposes is not required. The mobile handset is a relatively low cost and ubiquitous commercial device.

- These systems are able to estimate the position of mobile handsets operating on various first and second generation air-interfaces (AMPS - Advanced Mobile Phone Service, TDMA – Time Division Multiple Access, CDMA – Code Division Multiple Access, GSM - Groupe Spécial Mobile).

The disadvantages of wireless telephone positioning systems include:

- The signal structures used by mobile handsets are not optimized for positioning. In particular, the signals transmitted in AMPS are narrowband and TOA, and in particular AOA, estimation of these signals can seriously suffer from multipath.

- The receivers used to estimate TOA and AOA are generally installed in base stations of the wireless network. The geometry of these base stations is optimized for communications not positioning. As a result, DOP may be poor.

- For CDMA networks, it may be difficult for a sufficient number of base stations to hear the mobile handset due to strict power control imposed to overcome the near-far problem.

- Height estimation is generally not possible due to the poor vertical geometry of wireless networks.

- Solution bifurcation (two mathematically valid position solutions) caused by the relative distances between the receivers and the handset to be positioned is a significant problem.

Cambridge Positioning Systems employs E-OTD to position GSM handsets. In E-OTD, the mobile handset and a fixed receiver of precisely known position both estimate the TOA of a signal transmitted by a Base Transceiver Station (BTS). The position of the BTS is also precisely known. The time difference between the two TOAs is one observation. Therefore, at least four different BTS's are required for a 3D position fix. The fourth unknown is the clock offset of the mobile handset. E-OTD shares most of the above advantages and disadvantages of TOA and AOA systems.

Another network-based system which differs significantly from those described above was developed by U.S. Wireless Corporation. It is based on technology called RF fingerprinting which attempts to match the pattern of a received RF signal with that of patterns contained in a database. Associated with each pattern stored in the database is a location from which a mobile handset transmission will result in the said received signal pattern at a particular receiver location. The U.S. Wireless system consists of a number of receivers generally located in the wireless network base stations. However, only one receiver need hear a mobile handset transmission in order for a location to be estimated.

The primary pattern observed in the received signal is the group delay profile caused by multipath. See Wax and Leshem (1997) for the theory of estimating the multipath profile. The principle on which this system relies is that the multipath profile of the received signal is directly correlated to the position of the transmitter of the signal. An intensive calibration effort is required to generate the database of received signal patterns. This is a major disadvantage of this system. The major error source in this type of technology is the accuracy and resolution of the database. It is unclear how much the system accuracy suffers due to changes in the multipath environment caused by moving reflectors.

None of the systems reviewed in this section has the potential of yielding an accuracy of 1 m. Under the best circumstances they may result in a positioning accuracy of a few tens of metres.

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Grayson Wireless Website. URL: http://www.geometrix911.com/index.html

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Stilp, L., C. Knight, and J. Webber, (1994), *Cellular Telephone Location System*, July 5, U.S. Patent Number 5,327,144.

Wax, M., A. Leshem, (1997), *Joint Estimation of Time Delays and Directions of Arrival of Multiple Reflections of a Known Signal*, IEEE Transactions on Signal Processing, Vol. 45, No. 10, Oct., pp. 2477 – 2484.

2.3.1 Example System - TDOA Mobile Telephone Positioning

Table 5: Technology Profile for TDOA Mobile Telephone Positioning

Technology Characteristics	Principle of Operation	Mobile Phone TDOA
	Sensors	Cellular/PCS receivers that estimate TOA
	Observables	TOA
	Navigation Information Provided	3D position fix
	Other Characteristics	TOA estimation of signals transmitted by mobile. Network-based, Network overlay Passive GPS time synchronization of receivers All current cellular and PCS air-interfaces. Position calculated in network.
Operational Environment	Indoor and outdoor. Anywhere a mobile phone signal reaches the network.	
System Error Sources	Multipath Poor TOA estimation due to low received signal strength. Poor geometry. Timing synchronization.	
System Error Characteristics	For analog air-interfaces in particular, multipath is a major error source. Due to relative distances between receivers and the mobile solution, bifurcation a significant concern.	
A Priori Information	Precise position of fixed receivers required.	
Detectability	Signals are detectable but positioning by those signals is not.	
Limitations	Requires a minimum of four (for 3D fix) receivers to hear the mobile signal. Signal structure not necessarily optimized for positioning. Network geometry not necessarily optimized for positioning (in terms of geometry and the number of sites able to hear any particular mobile). No positioning possible when mobile switched off. Signal transmission from mobile may not be under control of network. Height estimation may be poor due to poor vertical geometry of most wireless networks.	
Advantages	Passive. Mobile is a relatively cheap and ubiquitous commercial device.	
Vendors	Cell-Loc, TruePosition	
Example Systems	Cellocate, TruePosition Wireless Location System	
Accuracy Performance (Stand-alone mode)	Analog air-interface (i.e. AMPS) 100-200 m Digital air-interface (i.e. CDMA) 10-90 m	

2.3.2 Example System - TDOA + AOA Mobile Telephone Positioning

Table 6: Technology Profile for TDOA + AOA Mobile Telephone Positioning

Technology Characteristics	Principle of Operation	Mobile Phone TDOA and AOA
	Sensors	Cellular/PCS receivers estimate TOA. Antenna array for AOA estimation.
	Observables	TOA and AOA
	Navigation Information Provided	3D position fix
	Other Characteristics	TOA and AOA estimation of signals transmitted by mobile. TDOA only or TDOA and AOA. Network based, Network overlay. All current cellular and PCS air-interfaces. Position calculated in network.
Operational Environment	Indoor and outdoor. Anywhere a mobile phone signal reaches the network.	
System Error Sources	Multipath (particularly on AOA) Poor TOA estimation due to low received signal strength. Poor geometry. Timing synchronization.	
System Error Characteristics	For analog air-interfaces in particular, multipath is a major error source (particularly for AOA). Due to relative distances between receivers and mobile, solution bifurcation a significant concern.	
A Priori Information	Precise position of fixed receivers required.	
Detectability	Signals are detectable but positioning by those signals is not.	
Limitations	Requires a minimum of two (for 2D fix) receivers to hear the mobile signal. Signal structure not necessarily optimized for positioning. Network geometry not necessarily optimized for positioning (in terms of geometry and the number of sites able to hear any particular mobile). No positioning possible when mobile switched off. Signal transmission from mobile may not be under network control. Height estimation may be poor due to poor vertical geometry of most networks.	
Advantages	Passive. Mobile is a relatively cheap and ubiquitous commercial device. AOA allows for positioning when fewer than the necessary number of receivers for TDOA positioning are able to hear the mobile.	
Vendors	Grayson Wireless	
Example Systems	Geometrix	
Accuracy Performance (Stand-alone mode)	Analog air-interface (i.e. AMPS) 100-200 m Digital air-interface (i.e. CDMA) 10-90 m	

2.3.3 Example System - E-OTD Mobile Telephone Positioning

Table 7: Technology Profile for E-OTD Mobile Telephone Positioning

Technology Characteristics	Principle of Operation	E-OTD (Enhanced Observed Time Difference). TOA of signal transmitted by BTS (Base Transceiver Station) measured at mobile and another fixed site of known position (gives one equation).
	Sensors	TOA receivers
	Observables	TOA
	Navigation Information Provided	3D position fix
	Other Characteristics	Require signals from four BTS's in order to generate a 3D position fix. GSM only at this time.
Operational Environment	Indoor and outdoor. Anywhere a mobile phone signal reaches the network.	
System Error Sources	Multipath Poor TOA estimation due to low received signal strength. Poor geometry.	
System Error Characteristics		
A Priori Information	Precise position of fixed receivers and transmitters required.	
Detectability	Signals are detectable but positioning by those signals is not. Transmission of TOA from mobile to network may be detectable.	
Limitations	Requires a minimum of four (for 3D fix) BTSs to transmit to the mobile and the fixed receiver of known position. Network geometry not necessarily optimized for positioning (in terms of geometry and the number of sites able to hear any particular mobile). No positioning possible when mobile switched off. Height estimation may be poor due to poor vertical geometry of most networks.	
Advantages	Timing synchronization not required since clock offset between the mobile and BTS's is solved for.	
Vendors	Cambridge Positioning Systems	
Example Systems	Cursor	
Accuracy Performance (Stand-alone mode)	15 m – 150 m	

2.3.4 Example System - RF Fingerprinting

Table 8: Technology Profile for RF Fingerprinting

Technology Characteristics	Principle of Operation	Pattern matching of received signal fingerprint.
	Sensors	RF receiver with RF signature capabilities.
	Observables	RF signature (primarily multipath signature)
	Navigation Information Provided	3D position fix is claimed. Unknown how system could be calibrated for height component.
	Other Characteristics	
Operational Environment	Indoor and outdoor. Urban and suburban environments. System performance unknown in rural environments where little multipath is present.	
System Error Sources	Changing multipath environment. Poor or incomplete system calibration. Obsolete calibration data.	
System Error Characteristics		
A Priori Information	Extensive calibration database correlated to each receiver/base station.	
Detectability	Signals are detectable but positioning by those signals is not.	
Limitations	Extensive calibration effort is required.	
Advantages	Positioning accomplished with only one receiver. Static multipath is not an error source.	
Vendors	U.S. Wireless Corporation	
Example Systems	RadioCamera™	
Accuracy Performance (Stand-alone mode)	According to US Wireless, RadioCamera™ meets the FCC E911 Mandate accuracy spec of 100 m (67%) and 300 m (95%).	

2.4 Other Terrestrial, Radiolocation Positioning Technologies

2.4.1 AM Broadcast Signals

Other methods of terrestrial positioning include the use of AM broadcast signals. Hall et al. (2001) have demonstrated instantaneous positioning of an AM receiver using carrier phase observations. This method is very similar to carrier phase differencing of GPS signals. The AM receiver to be positioned estimates the frequency, phase, and magnitude of several different AM broadcast signals. A second receiver, at a known, fixed location, does the same. The observed phase difference for each transmitter is calculated and these phase differences constitute the system's observations.

To overcome the ambiguity inherent in carrier phase measurements, Hall et al. search the position space to maximize a function based on the observed phase differences and the known positions of the AM transmitters. Continuous tracking of the AM signals is not required.

Advantages of AM-based systems include:

- no deployment of a transmitter network is required; existing AM broadcast transmitters are used;
- long wavelength AM signals are less susceptible to multipath;
- AM signals penetrate buildings well and generally have high SNR.

Positioning with AM signals does have disadvantages as well. The propagation of AM ground waves varies according to the conductivity and permittivity of the ground, and sky waves may interfere with ground waves at night. The error source of most concern, however, is phase distortion due to conductors in the vicinity of the receivers. This is particularly true indoors. Hall et al. report phase errors of several radians on phase measurements made indoors.

For outdoor receivers, Hall et al. have demonstrated position accuracies of a few metres over baselines of several hundreds of metres. Documented indoor position results are not available at this time.

Reference:

Hall, T., C. Counselman, and P. Misra, (2001), *Instantaneous Radiolocation Using AM Broadcast Signals,* Proceedings of ION National Technical Meeting, Long Beach California, Jan. 22 – 24, pp. 93-99.

Table 9: Technology Profile for AM Broadcast Positioning

Technology Characteristics	Principle of Operation	Carrier Phase of AM Broadcast Signals
	Sensors	AM radio receiver with signal processing
	Observables	Carrier phase
	Navigation Information Provided	2D position fix
	Other Characteristics	Carrier phase difference between mobile receiver and fixed receiver of known position. Maximization of ambiguity function. Instantaneous relative position vectors. Continuous tracking not required.
Operational Environment	Outdoor (Indoor to be tested in future)	
System Error Sources	Propagation speed of groundwaves varies with conductivity and permittivity of ground. Skywave interference at night. Phase distortion due to nearby conductors.	
System Error Characteristics		
A Priori Information	Precise position of fixed receiver.	
Detectability	Location calculated at AM receiver and needs to be transmitted back to interested parties.	
Limitations	Indoor use and accuracy are limited due to phase corruption by nearby conductors. Coverage area limited to AM radio coverage areas.	
Advantages	Long wavelength AM signals less susceptible to multipath. Makes use of existing AM broadcast signals. Excellent building penetration. High SNR.	
Vendors	None	
Example Systems	Hall et. al. (2001)	
Accuracy Performance (Stand-alone mode)	Few metres over several hundred metres.	

2.4.2 Received Signal Strength

The strength of received signals may also be used to estimate the position of a transmitter. There are two modes in which received signal strength may be used. In the first, received signal strength is used as an indicator of AOA. This is essentially the concept of direction finding. Using an antenna that is physically or electronically 'steered', the AOA of a signal transmitted by the device to be positioned and received at a particular receiver site is estimated as that direction which yields the highest signal strength. This approach suffers from the same disadvantages as AOA positioning – in particular, blockage of the direct signals and propagation of multipath signals can cause very large errors in the AOA measurement.

A second approach to using received signal strength involves the concept of proximity detection. As a small mobile transmitter moves through a coverage area, multiple fixed receivers of known position receive the transmitter's signal. The position of the transmitter is estimated based on the received signal strength at each receiver. This estimation may be as simple as the location of the receiver with the highest received signal strength or it may be based on a combination of the receiver locations weighted by the received signal strengths. In any case, the accuracy of such a system is directly correlated to the number of receivers and the distances between them.

A commercial system based on received signal strength is offered by Sovereign Tracking Systems LLC (www.sovtechcorp.com). The PalTrack system is marketed as a real time tracking product for assets and personnel. Details regarding the nature of the system (other than the use of received signal strength), its accuracy, and its operational environment are very limited. The information in the table below is with respect to the PalTrack system. Note that the accuracy specified is not claimed by Sovereign Technologies LLC, but by Pahlavan et al. (2000).

References:

Pahlavan, K, X. Li, M. Ylianttila, R. Chana, and M. Latva-aho (2000), *An Overview of Wireless Indoor Geolocation Techniques and Systems,* Online publication, May 12, http://www.link.springer-ny.com/link/service/series/0558/bibs/1818/18180001.htm.

Sovereign Tracking Systems LLC Website. URL: http://www.sovtechcorp.com

Table 10: Technology Profile for Received Signal Strength Positioning

Technology Characteristics	Principle of Operation	Location by received signal strength at a number of receivers.
	Sensors	Receivers
	Observables	Received signal strength
	Navigation Information Provided	Position (2D)
	Other Characteristics	Miniature tag transmitters Signal structure unknown (codes) 418 MHZ or 433.9 MHz
Operational Environment	Indoors only	
System Error Sources	Multipath, Signal attenuation	
System Error Characteristics	Accuracy and resolution highly dependent on number and placement of proximity receivers.	
A Priori Information	Precise location of receivers	
Detectability	unknown	
Limitations	Distance, Not outdoor	
Advantages	Very small transmitter.	
Vendors	Sovereign Technologies LLC	
Example Systems	PalTrack	
Accuracy Performance (Stand-alone mode)	0.6 to 2 4 m (according to Pahlavan et. al. 2000)	

2.5 Standard Global Positioning System (GPS)

GPS has become the standard navigation system for most marine, air and land applications where line-of-sight is available. The system specifications are well documented in the literature. The 1.5 GHz carrier frequency, modulated by a CDMA technique, results in high measurement resolution. Sub-metre level positioning accuracies are routinely achieved. One of the two main reasons for such a high level of performance is that signals travel along a straight line (shortest distance) between the satellite-based transmitters and the user's antenna. As soon as this **straight-line propagation principle** breaks down, accuracy degrades. The other reason is that a sufficient number of satellites are available to provide good positioning geometry. Thus, in an urban outdoor environment where signal reception is clear in one hemisphere but completely blocked in the other, accurate positioning is simply not possible.

The satellites are located 20,000 km in space. The signals experience a 180 dB loss as a result of free-space propagation. Given this and the low penetration capability of 1.5 GHz signals through material, GPS signals cannot generally be received indoors due to signal acquisition and tracking limitations. Occasionally indoor reflected (multipath) signals can be measured by a standard GPS receiver that has first acquired the signals outside. However, since the above straight line propagation principle no longer applies, accuracy degrades accordingly.

Standard GPS is, therefore, not a candidate for indoor location.

References:

Parkinson, B.W., et al (1996), *GPS: Theory and Applications*, Progress in Astronautics and Aeronautics, Vol. 163, American Institute of Aeronautics and Astronautics, Washington, D.C.

Institute of Navigation (1987-present), Proceedings of Annual GPS conferences organized by the U.S. Institute of navigation, Alexandria, VA. (www.ion.org).

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Table 11: Technology Profile for Standard GPS Positioning

Technology Characteristics	Principle of Operation	Satellite-based time-synchronized transmitters, 1.5 GHz, CDMA
	Sensors	RF receivers
	Observables	Ranges and carrier phase
	Navigation Information Provided	3D + accurate timing
	Other Characteristics	
Operational Environment	All-weather, line-of-sight, worldwide coverage, 24-hours per day	
System Error Sources	Satellite (clocks and orbits), atmospheric propagation delay errors, receiver (noise, multipath), interference, satellite geometry degradation under signal masking conditions (e.g. urban canyons)	
System Error Characteristics	Satellite and propagation errors can be largely removed by differential operation. Carrier phase mode can deliver cm-level accuracy under appropriate outdoor conditions	
A Priori Information	Satellite positions transmitted in navigation messages	
Detectability	GPS signals are available everywhere in open space near earth	
Limitations	No indoor capability	
Advantages	Coverage, availability and high accuracy outdoors	
Vendors	Hundreds, cost (what does cost mean here?)	
Example Systems	NovAtel, Trimble, Magellan, Garmin, SiRF, etc	
Accuracy Performance (Stand-alone mode)	10-20 m single point cm to 1-m level in differential mode	

2.6 Stand-Alone High Sensitivity (HS) GPS

Stand-alone high sensitivity GPS receivers use proprietary or patented techniques to increase the otherwise low signal-to-noise ratio (SNR) prevailing under signal masking conditions. Signal integration until the SNR is well above 0 dB is carried out using specialized tracking loop firmware. Certain reflected (multipath) and refracted (through certain materials) signals can be measured. Applications are still limited to certain types of buildings that allow 1.5GHz signal penetration. The straight-line propagation principle does not apply to multipath signals and weak refracted signals, both of which result in lower measurement resolution. In most buildings, satellites from certain directions cannot be measured at all due to denser material, resulting in geometry degradation. As a consequence, positioning accuracy is of the order to 20 – 100 m at this time. In the case of vehicular applications, trajectory constraints on the filter can improve accuracy. This is not, however applicable to personnel location.

Stand-alone High Sensitivity GPS is not a candidate for indoor location at this time. However, as the technology evolves, this approach may become viable for wooden construction and low rise buildings if integrated with self contained sensors.

References:

van Diggelen, F. (2001), *Indoor GPS*, Navtech Lecture, GPS 01 Conference, Salt Lake City, September 10-11.

Lachapelle, G. et al (2002), *Degraded GPS Signal Measurements with a Stand-Alone High Sensitivity Receiver*, To be presented at the National Technical Meeting, U.S. Institute of Navigation, San Diego, Jan 28-30.

Table 12: Technology Profile for Stand-alone High Sensitivity GPS Positioning

Technology Characteristics	Principle of Operation	Satellite-based time-synchronized transmitters, 1.5 GHz, CDMA
	Sensors	HS RF receivers
	Observables	Ranges and carrier phase
	Navigation Information Provided	3D or 2D + accurate timing
	Other Characteristics	
Operational Environment	All-weather, line-of-sight, worldwide coverage, 24-hour per day	
System Error Sources	Same as standard GPS, plus multipath and weak signal measurements, poor geometry.	
System Error Characteristics	Weak signals result in poorer resolution. Multipath signals result in non line of sight measurements. Satellite availability adversely affects geometry.	
A Priori Information	Satellite positions transmitted in navigation messages	
Detectability	GPS signals are available everywhere in open space near earth	
Limitations	Low accuracy at this time, available only under relatively benign indoor conditions (e.g. wooden buildings)	
Advantages	GPS signals available worldwide provided they can be detected and measured	
Vendors	SiRF plus other emerging vendors	
Example Systems	SiRF (see Lachapelle et al 2002)	
Accuracy Performance (Stand-alone mode)	20- 100 m in certain building types	

2.7 Network-Aided High Sensitivity GPS

In recent years, there has been much motivation to use GPS in challenging environments such as indoors. The desire to track the location of rescue or military personnel indoors as well as wireless telephone callers to 911, has produced the need for indoor GPS. Standard GPS receivers are not able to function indoors due to signal strength limitations. In order to acquire satellite signals in a reasonable length of time (less than one minute), the receiver is only able to search each frequency/code bin for 1 ms. The dimensions of the acquisition search space are frequency (due to Doppler from satellite motion) and code delay (1023 C/A code bits). Given no extra information, the receiver must search all the frequency/code bins in order to acquire a satellite's signal. With an integration time of only 1 ms, the minimum satellite signal strength at which the receiver can acquire is approximately –130 dBm. This is the satellite signal strength in the open at the earth's surface. Since satellite signals may suffer attenuation in excess of 30 dB when passing through walls of structures, standard GPS receivers are not able to acquire the signals indoors.

One key to acquiring low power satellite signals is long integration times. The C/A code is repeated every 1 ms. By accumulating many 1 ms copies of the code the SNR (Signal to Noise Ratio) is improved to the point that a low power signal may be detected. Peterson et al. (1997) were one of the first to acquire GPS signals indoors with long integration times. They report that with integration times of 80 to 160 ms, indoor GPS signals with signal strengths as much as 28 dB less than outdoor signals, could be measured. In order to integrate for this long however, the GPS receiver requires information it usually receives from the satellites, from some alternate source. This information includes the satellite almanac and ephemeris which are transmitted by the satellites in the 50 bps navigation message. Because of the slow data rate, the navigation message cannot be integrated. Hence, it cannot be received indoors and must be provided from some other source.

In order to reliably receive GPS satellite signals indoors, a GPS receiver requires (see van Diggelen, 2001):

- satellite ephemeris
- GPS time
- a calibrated local oscillator
- receiver velocity
- receiver position

Note that knowledge of the Doppler frequency for each satellite is critical for narrowing down the frequency/code search space. Obviously, the above information is received or determined by observing the satellites' signals. Wireless-aiding or network-aiding seeks to provide as much of this information as possible by some communication means other than GPS satellites. This may be accomplished by observing the satellite signals with a receiver with clear view of the sky and

communicating this information to the indoor GPS receiver via a communication link such as wireless telephony.

In addition to wireless or network-aiding, massive parallel correlation is required to reliably receive GPS satellite signals indoors. Knowledge of the satellite's Doppler frequency narrows the frequency search space. All possible code delays, however, must still be searched. A large number of correlators are required to integrate over a sufficiently long period of time, at all possible code delays, of all satellites desired. Massive parallel correlation may be implemented in software or hardware. SnapTrack was one of the first companies to implement in software a network-aided GPS receiver with massive parallel correlation (see Moeglin and Krasner, 1998, and Krasner, 1997). Other vendors such as SiRF have implemented hardware solutions (see Chansarkar and Garin, 2000, and Shewfelt et. al., 2001). A number of other vendors also offer network-aided GPS chipsets including Global Locate, Parthus, and SigTec.

Many vendors of indoor GPS receivers and chip sets have demonstrated increased sensitivity to the point that typical accuracies of 20 m to 100 m are achieved inside a wide variety of structures. Multipath continues to be a major error source for network-aided, high sensitivity GPS receivers. In fact, Peterson et al. (1997) state that the majority of signals received indoors are multipath signals. Movement of the receiver is also a source of performance degradation. In addition to limiting the length of possible coherent integration, velocities greater than 0.5 m/s require near real-time knowledge of the satellite Doppler frequency.

References:

Chansarkar, M., and L. Garin, (2000), *Acquisition of GPS Signals at Very Low Signal to Noise Ratio,* Proceedings of ION National Technical Meeting, Anaheim, California, Jan. 26-28, pp. 731-737.

Global Locate Website. URL: http://www.globallocate.com/

Krasner, N. (1997), *GPS Receiver and Method for Processing GPS Signals,* U.S. Patent Number 5,666,734, Sept. 2.

Moeglin, M., and N. Krasner, (1998), *An Introduction to SnapTrack Server-Aided GPS Technology,* Proceedings of ION GPS-98, Nashville, Tennessee, Sept. 15-18, pp.333-342.

Parthus Website. URL: http://www.parthus.com

Peterson, B., D. Bruckner, and S. Heye, (1997), *Measuring GPS Signals Indoors*, Proceedings of ION GPS-97, Kansas City, Missouri, Sept. 16-19, pp. 615-624.

Shewfelt, J., R. Nishikawa, C. Norman, and G. Cox, (2001), *Enhanced Sensitivity for Acquisition in Weak Signal Environments Through the Use of Extended Dwell Times,* Proceedings of ION GPS-01, Salt Lake City, Utah, Sept. 11-14.

SigTec Navigation Website. URL: http://www.signav.com.au

SiRF Website. URL: http://www.sirf.com

van Diggelen, F. (2001), *Indoor GPS*, Navtech Seminars course 218, presented in San Diego, California, March.

Table 13: Technology Profile for Network-Aided High Sensitivity GPS Positioning

Technology Characteristics	Principle of Operation	High Sensitivity GPS receivers aided by a wireless network.
	Sensors	GPS receiver
	Observables	pseudoranges
	Navigation Information Provided	3D position fix + accurate timing
	Other Characteristics	Acquisition of low level GPS signals accomplished using data provided from a wireless network. Provided data may include - Almanac - Ephemeris - GPS time - Doppler - Approximate receiver position Network-aiding may be combined with massive parallel correlation for reliable indoor performance.
Operational Environment	Outdoor and certain indoor locations.	
System Error Sources	Multipath	
System Error Characteristics	Heavily dependent on information provided by wireless network.	
A Priori Information	Information received from wireless network.	
Detectability	Wireless aiding data may be detected.	
Limitations	Limit to the receiver sensitivity obtained. Receiver motion may necessitate real time Doppler updates.	
Advantages	All the advantages of standard GPS plus the fact that it works in areas that standard GPS does not.	
Vendors	Qualcomm (SnapTrack), SiRF, Global Locate, Parthus, SigTec	
Example Systems		
Accuracy Performance (Stand-alone mode)	20 m – 100 m (indoors, various structures)	

2.8 GPS Pseudolites

A pseudolite (pseudo-satellite) is a ground-based transmitter that is capable of transmitting GPS signals. They can be used to augment GPS satellite signals to improve geometry, as in the case of aircraft landing where a pseudolite below the aircraft significantly improves the vertical geometry (e.g. Cobb et al., 1995), or they can be used where there may be significant satellite shading effects, as in the case of mining. Since the location of the pseudolite is user-selectable (within operational constraints), it can be placed in strategically important areas to maximize effectiveness. The receiver must be capable of receiving pseudolite information as this is not a standard feature of off-the-shelf receivers. Currently, the NovAtel series of receivers (MiLLennium and after) are the only receivers that have this capability. Some limited tests have been done with other receivers.

Alternatively, if at least four pseudolites are available, a GPS receiver can position itself with respect to the pseudolites alone, without directly tracking GPS satellites. As discussed later, the performance of this scenario is a function of the geometry of the pseudolites relative to the user, and the received signal quality.

As an alternative to the above, pseudolites can be used in an inverted mode whereby a 'constellation' of receivers tracks a mobile pseudolite in a local area. The concept of inverted pseudolite positioning was first presented by Raquet et al. (1995). In their experiment, a ground-based test was conducted to determine the feasibility of using mobile pseudolites for precise positioning of military aircraft. For such a system to work, the reference receivers must be arranged in a suitable geometry and have well-determined relative coordinates. A reference pseudolite is also required to provide a reference clock and to allow between-pseudolite single differencing (analogous to between-receiver differencing in standard DGPS). The location of the reference pseudolite should be chosen such that all receivers have a line-of-sight capability. O'Keefe et al. (1999), demonstrated this technique for short range positioning within a 50 m^2 area.

A pseudolite can transmit both code and carrier phase information, and can also transmit other types of data such as differential GPS corrections. However, the region over which these signals can be used is a function of the near/far problem. This problem is a result of the potential cross-correlation of the pseudolite signals with GPS signals, which can be controlled to some extent by limiting the range from the pseudolite in which the receiver operates. A pseudolite transmitting a standard GPS signal will jam all channels inside a near radius and will not be detected outside a far radius approximately ten times the near radius (O'Keefe et al., 1999). This is due to the fact that power levels of the received signals will be different depending on the geometry of the receiver with respect to the transmitting pseudolite. Since compared to a satellite the pseudolites are quite close to the receiver, a small movement can cause large changes in the received power levels (received signal power level is inversely proportional to the square of the range from the transmitter to the receiver).

The near/far problem can be reduced through the use of a pulsing scheme for the pseudolite signal (e.g. Kee et al., 2000). Duty cycles of 10%-30% are typical, which means that the signal is

transmitted for 10%-30% of the time (Farley and Carlson, 1998). The signals can be tracked with the reduced duty cycle through an increase in the signal power.

In order to utilize pseudolites, the signals must be time synchronized with GPS time. In order to achieve this, some systems have used a GPS receiver at the pseudolite location to provide time synchronization capability (Farley and Carlson, 1998).

Multipath errors can reach several ten's of metres indoors and can oscillate 100 m from measurement to measurement (e.g. Farley and Carlson, 1998). In some cases, helical antennas have been used to mitigate multipath (Kee et al., 2000). The latter authors demonstrated the concept of using pseudolites mounted within a single room to locate an object moving within a small area of that room. No transmission through walls was tested. Multipath was reduced through the use of highly directional antennas. Such an approach is not applicable to a person moving randomly within and/or between rooms.

The location of the pseudolite must be known prior to usage of the system. This is equivalent to the requirement for ephemeris information when using GPS satellites. In the case of pseudolites, the location is generally fixed, so a presurvey can be done to determine the absolute position of the pseudolite. Self-survey capabilities have also been developed (e.g. Farley and Carlson, 1998; Kee et al., 1999). Any error in the absolute position of the pseudolite will result in an error in the user's position, of which the magnitude is a function of the survey error and the user's geometry with respect to the pseudolite(s).

The advantage that pseudolites would have over satellites for indoor location is that the transmitted signal power can be increased at will without swamping GPS channels if one assumes that the pseudolites are mounted outdoors and the receiver is indoors and thus receive only pseudolite signals. No emission takes place from the indoor user in this case. GPS technology and equipment is thus used without the use of actual GPS satellites. The near/far problem disappears. A higher power enables the 1.5 GHz signals to more effectively penetrate material. No related experimental results have been found in the literature. An initial performance analysis of such a system would not be difficult to initiate for an engineering group familiar with GPS and pseudolites. (A disadvantage of this scheme is that the pseudolites would jam other GPS receivers used in the area – perhaps by other troops working outside the building of interest).

In terms of pseudolite systems, there are no manufacturers currently selling systems on a commercial basis. Integrinautics has produced pseudolites in the past but are in the process of possibly terminating this part of their business. Although Rockwell has developed some prototype systems (e.g. Tuohino et al., 2000), these are not available commercially as of yet.

References:

Cobb, H.S, C.E. Cohen and B.W. Parkinson (1994), *Theory and Design of Pseudolites*, Proceedings of ION NTM-94, San Diego, January 24-26, pp. 69-75.

Cobb, H.S., D. Lawrence, B. Pervan, C. Cohen, J.D. Powell and B.W. Parkinson (1995), *Precision Landing Tests with Improved Integrity Beacon Pseudolites*, Proceedings of ION GPS-95, Palm Springs, September 12-15, pp. 827-833.

Farley, M.G. and S.G. Carlson (1998), *A New Pseudolite Battlefield Navigation System,* Proceedings of IEEE PLANS, pp. 208-217.

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Michalson, W.R., and I.F. Progri (2000), *Assessing the Accuracy of Underground Positioning Using Pseudolites,* Proceedings of the ION GPS-00, Salt Lake City, September 19-22, pp. 1007-1015.

O'Keefe, K., J. Sharma, M.E. Cannon and G. Lachapelle (1999), *Pseudolite-based Inverted GPS Concept for Local Area Positioning,* Proceedings of ION GPS-99, Nashville, September 13-17, pp. 1523-1529.

Progri, I.F. and W.R. Michalson (2001), *An Alternative Approach to Multipath and Near-Far Problem for Indoor Geolocation Systems,* Proceedings of the ION GPS-01, Salt Lake City, September 11-14, (in press).

Progri, I.F., J. Orr and D. Cyganski (2000), *A System for Tracking and Locating Emergency Personnel Inside Buildings,* Proceedings of the ION GPS-00, Salt Lake City, September 19-22, pp. 560-568.

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Tuohino, J.L., M.G. Farley and R.R. James, (2000), *Military Pseudolite Flight Test Results,* Proceedings of ION GPS-00, Salt Lake City, September 19-22, pp. 2079-2088.

Table 14: Technology Profile for GPS Pseudolite Positioning

Technology Characteristics	Principle of Operation	Ground transmitter of GPS-like signals
	Sensors	Spread-spectrum receiver
	Observables	Code and carrier phase data
	Navigation Information Provided	Used to augment or replace satellite signals Still require GPS receiver
	Other Characteristics	
Operational Environment	Can operate indoors and outdoors. May require modified antenna (helical) for improved indoor performance.	
System Error Sources	Near-far problem Multipath Tropospheric effects	
System Error Characteristics	Near/far problem Multipath Survey errors	
A Priori Information	Precise location of pseudolite (pre-surveyed)	
Detectability	Generally high as it transmits coherent signal including location	
Limitations	Significant multipath effects indoors	
Advantages	Location(s) can be user-selectable within geometry constraints Easily deployed	
Vendors	Integrinautics, although they are stopping production. Rockwell	
Example Systems	IntegriNautics IN200C™ L1 pseudolites, Rockwell's Battlefield Navigation System (not a production system)	
Accuracy Performance (Stand-alone mode)	Using a stand-alone GPS receiver, performances of several metres to over 100 m (in high multipath environments) have been reported.	

2.9 Loran-C

Loran-C is a long range RF system operating in a bandwidth centred on 100 kHz. The transmitted power ranges from 300 to 1,000 kW. Due to diffraction and ground conductivity, the ground wave bends along the transmission path, extending the range to well beyond the horizon. The range varies between hundreds and 2,000 km, the longest range being at sea, due to the superior conductivity of sea water. Three to five ground-based transmitters form a chain that covers a typical area of 2,000 x 2,000 km. The continuous carrier wave is modulated by an amplitude modulated pulse. Emission synchronization is ensured by atomic frequency and time standards (FTS) at each transmitter. The FTS are inter-compared on a quasi-continuous basis to maintain synchronization between transmitters. Pulse envelope and cycle matching yields a range difference resolution on the order of 1 to 2 m under ideal conditions. The outdoor repeatable accuracy can reach 5 m but is affected by seasonal ground conductivity variations and weather fronts. These two effects can be removed using a differential technique. With advanced digital receivers, differential Loran-C may be able to yield an accuracy slightly better than 5 m. Availability and performance can, however, be affected by atmospheric and human-made noise.

The 100 kHz wave can penetrate dense urban environments and many types of buildings. As with any other RF system, however, the actual accuracy degradation level will be a function of material type and other building characteristics, in addition to interference in the 100 kHz range. Receiver technology has improved during the past 15 years. Locus, Inc., of Madison Wisconsin, claims that its patented Linear Averaging Digital (LAD) technology, which includes digital noise blanking and DSP techniques, has a high degree of penetration and resistance to interference in urban canyons. Its receivers retail for about US $7,000 a piece. The company makes no statement as to indoor performance. There is little doubt that Loran-C can operate under numerous indoor conditions with this type of technology. No systematic investigation, however, is publicly available on the subject. Investigating indoor performance would be fairly straightforward.

Loran-C overage and maintenance is the responsibility of coast guards or their equivalent in many countries where Loran-C exists, including Canada and the USA. The entire continental USA and the southern part of Canada are covered by the system. Having been deployed primarily for marine navigation, Loran-C coverage is sporadic around the world and is usually limited to coastal regions. The Canadian Coast Guard has been investigating the possibility of discontinuing its Loran-C service. The North European have deployed Eurofix during recent years and many groups are initiating indoor location experiments.

Although the potential of Loran-C to deliver an indoor accuracy of 1-2 m is extremely low, integration of the system with other systems/sensors may be an option.

References:

Appleyard, S.F., et al (1988), *Marine Electronic Navigation*, Routledge & Kegan Paul, London, ISBN 0-7102-1271-2, 2nd Ed.

Bowditch, N. (1995), *American Practical Navigator, 1995 Edition*, Pub. No. 9, Defense Mapping Agency Hydrographic/Topographic Center, USA, DMA Stock No. NVPUB9V1.

Canadian Coast Guard (2001), *Impact Study of the Proposed Discontinuance of Canada's Loran-C Radionavigation Service*. http://www.ccg-gcc.gc.ca/loranc/main.htm

Frank, R. (1983), *Current Developments in Loran-C*, Proceedings of IEEE, Vol. 71, 10.

Lachapelle, G., et al (1992), *Analysis of Loran-C Performance in the Pemberton Area, B.C.*, Canadian Journal of Aeronautics, Canadian Aeronautics and Space Institute, Vol. 38, No. 2, pp. 52-61.

Lachapelle, G., et al (1993), *GPS/Loran-C: An Effective System Mix for Vehicular Navigation in Mountainous Areas*. Navigation, Vol. 40, No. 1, The Institute of Navigation, Alexandria, VA, pp. 19-34.

Samaddar (1979), *The Theory of Loran-C Ground Wave Propagation*, Navigation, The U.S. Institute of Navigation, Vol. 26, No 3.

U.S. Coast Guard (1992), *Loran-C Users Handbook 1992 Edition*, U.S. Coast Guard Radionavigation Division, www.navcen.uscg.gov/loran

Table 15: Technology Profile for Loran-C

Technology Characteristics	Principle of Operation	TDOA
	Sensors	100 kHz RF system
	Observables	range differences (hyperbolic)
	Navigation Information Provided	2D Horizontal
	Other Characteristics	Over-the-horizon system
Operational Environment	Ground-based 100 kHz transmitters, range of up to 2,000 km, all weather	
System Error Sources	TDOA resolution, ground conductivity and weather fronts, RF interference (both outdoors and indoors).	
System Error Characteristics	TDOA resolution is limited due to long frequency of system. Ground conductivity variations and weather front effects can easily be taken out by differential method. A fair amount of human-made noise is generated at 100 kHz	
A Priori Information	Loran-C chain information (transmitter location, pulse characteristics, etc) are loaded in each receiver	
Detectability	Loran-C signals are present everywhere coverage exists	
Limitations	Measurement resolution is limited (due to low frequency). It is highly doubtful that the system has the potential of reaching an accuracy of 1 m indoors. Integration with other systems is an option however. Limited to Loran-C coverage areas.	
Advantages	Easy to obtain 5-10 m repeatable accuracy. Will operate in urban canyons (but accuracy would likely be degraded). Low receiver cost	
Vendors	Locus, Inc, Madison, WI, offers high performance receivers	
Example Systems	Loran-C chains cover the entire continental United States and the southern part of Canada	
Accuracy Performance (Stand-alone mode)	5-10 m repeatable accuracy, better than 5 m in differential mode outdoors. Indoor accuracy would be a function of the material environment.	

2.10 Inertial Technology

Inertial Navigation Systems (INS) made their appearance in commercial aviation in the late sixties and have been used extensively in intercontinental navigation and in flight control systems. Their distinctive characteristic is the capability for autonomous navigation in any environment. They operate without reference to external signals and, therefore, are not affected by atmospheric conditions, line of sight obstructions or underwater or underground operation. This feature attracted major military research funding and the vigorous development of inertial components and systems over the last thirty years can be mainly attributed to this interest (Krakwisky et al., 1990). At present, there is no sign that this development is showing down. For more details on the future of inertial navigation systems see Schwarz and El-Sheimy (1998).

The principle of inertial navigation is based on Newton's first and second laws of motion. By measuring vehicle acceleration in an inertial frame of reference, integrating it with respect to time and transforming it to the navigation frame, velocity, attitude and position differences in the navigation frame can be obtained. In this mode of operation, an INS can be considered a highly sophisticated dead-reckoning system. Sensors used to implement such a system are accelerometers for the measurement of specific force and gyroscopes for the implementation of an inertial frame of reference. Since specific force measurements contain the effect of the gravity field of the earth, a gravity model is needed to extract vehicle acceleration from the measurements. Because they employ three translational and three rotational sensors, inertial measuring units can be used as attitude sensing devices as well.

The INS measures linear acceleration and angular rates very accurately and with minimum time delay. For short time intervals, the integration of acceleration and angular rate results in extremely accurate velocity, position, and attitude with low noise and negligible time lag. However, because INS position and velocity are obtained by integration, they are subject to adverse effects by low frequency errors. Because of the time integration, the INS position and velocity errors grow with time, a typical error behaviour that in many ways delineates the areas of potential applications as a stand-alone system. Furthermore, to achieve the required accuracy in this project with a stand-alone INS system, a navigation grade INS, which are very expensive Even navigation-grade INS (≈ $100,000 US) will not achieve the required accuracy for this project without aiding; for example by GPS positions or frequent Zero-Velocity-Update (not practical for indoor navigation). For a discussion of the principle of operation, see Merhav (1996), status of inertial technology, see Greenspan (1995) and Barbour (1996), trends in inertial technology, see Hulsing (1998) and for integration with GPS, see Rogers (2000.

References:

Barbour, N. (1996), *Status of Inertial Systems*, Paper presented at ION National Technical Meeting January 22-24, 1996, California.

Greenspan, R. (1995), *Inertial Navigation Technology from 1970-1995*, Journal of the Institute of Navigation, Vol. 42, No. 1, Special Issue.

Hulsing, R. (1998), *MEMS Inertial Rate and Acceleration Sensor*, Proceedings of IEEE PLANS 1998, pp. 169-176.

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Krakiwsky, E. J., G. Lachapelle, and K.-P. Schwarz (1990), *Assessment of emerging technologies for future navigation systems in the Canadian transportation sector*, Technical Report UCSE Report No. 60007, The University of Calgary, Department of Surveying Engineering.

Merhav, S. (1996), *Aerospace Sensor Systems and Applications*, Springer-Verlag, New York.

Schwarz, K.P., and El-Sheimy, N., *Future Positioning and Navigation Technologies*, Study performed under the Scientific Services Agreement with Batelle (contract no. DAAH04-96-C-0086), Columbus Division and Topographic Engineering Center, Fort Belvoir, VA, USA

Rogers, R.M. (2000), *Applied Mathematics in Integrated Navigation Systems*, AIAA Education Series, 2000.

Table 16: Technology Profile for Inertial Positioning

Technology Characteristics	Principle of Operation	Dead Reckoning using acceleration and angular velocities
	Sensors	Gyroscopes, Accelerometers
	Observables	Specific force and angular velocity in each of the three direction components
	Navigation Information Provided	Position, velocity and attitude
	Other Characteristics	Global, Autonomous
Operational Environment	All environments including buildings, underground, and underwater	
System Error Sources	Gyro bias and scale factor, accelerometer bias and scale factor, sensor assembly errors, errors in initial conditions.	
System Error Characteristics	Horizontal position errors consist of periodic errors (Schuler with a period of 84 minutes) superimposed by drift errors which grow in an unbounded fashion. Height errors are unbounded and grow rapidly.	
A Priori Information	Initial position, earth rotation rate and gravity field of the Earth	
Detectability	Not detectable	
Limitations	High cost, heavy weight, sensor sensitivity. Uncertainty in the gravity field of the Earth	
Advantages	Not detectable, passive, self-contained, continues navigation, high data rate	
Vendors	Litton, Honeywell, SEGEM, Rockwell (Boeing)	
Example Systems	LTN-20X family, Honeywell-LaserReff-III family, Rockwell - CMIGITS, Motion-back	
Accuracy Performance (Stand-alone mode)	1. INS/RLG zero lock o Free inertial: 0.8/0.6 nmi/h, 0.5 nmi/h after enhanced alignment o With 3-4 min ZUPTs < 2 m 2. FOG-based o Free inertial: < 1.0 nmi/h o With 3-4 min ZUPTs: 15 – 20 m 3. Digital Quartz Inertial (DQI) based o System accuracy not reported. Free inertial > 10 m/min o With ZUPTs: no significant improvement expected	

2.11 Micro-electromechanical Sensors (MEMS)

It is outlined in U.S. DoD, (1995) that MEMS product developments are driven by *miniaturization*, *multiplicity* and *microelectronics*. There are many advantages to having *miniature* sensors and systems. From a practical sense, smaller often implies easier to carry or to supply with power: features that may be crucial in the case of a personal navigation system. In a physical sense, smaller and lighter can mean higher resonant frequencies (and in turn higher operating frequencies and bandwidths) and shorter thermal time constants to name a few examples. *Multiplicity* is attractive because it makes production easier and cheaper. It is also very important because it implies that systems that run in parallel might be more easily produced, e.g. arrays of sensors. With recent advances in *microelectronics*, it is possible to combine intelligent electronics on the same chip as the sensors, resulting in relatively complex and advanced systems. As we will see, examples of this are closed loop accelerometers and complete single chip IMU designs.

In the world of inertial navigation, the advantages of MEMS based sensors and systems are obvious. Weight, size, power consumption, survivability and cost are all parameters that can be reduced considerably. Companies and institutions all over the world are working to see how much they can use MEMS while maintaining acceptable levels of accuracy. It has become clear that three scenarios exist for the development of an IMU that is cheaper, lighter and uses less power. These are

- A lightweight IMU based on improving current sensor technologies (e.g. IFOG, VBA),
- A lightweight IMU based on emerging MEMS sensor technologies and
- A fully integrated MEMS IMU on a chip.

Like their traditional counterparts, MEMS accelerometers are based on either the principle of force rebalance or resonant elements. All current MEMS gyroscopes are based on the Coriolis principle. The rapid development of Micro-electromechanical (MEMS) inertial sensors in the last decade has clearly been driven by certain factors. These include technological advances in miniaturization, new materials and large scale funding for commercial and military applications. It is apparent that accelerometer development is more mature than gyro development, due primarily to the push for reliable crash detectors in the automobile market. Therefore, as far as MEMS IMU development is concerned, it is gyro development that limits the achievable accuracy. For principle of operation, see DARPA (1998) and for an example of MEMS-based IMU systems, see Davis (1998).

References:

DARPA (1998), *Microelectromechanical Systems (MEMS)*, Electronics Technology Office, DARPA, http://web-ext2.darpa.mil/eto/mems/index.

Davis, B.S. (1998), *Using low-cost MEMS accelerometers and gyroscopes as strapdown IMUs on rolling projectiles*, Proceedings of IEEE PLANS 1998, pp 594-601.

U.S. D.o.D. (1995), *Microelectromechanical Systems Opportunities*, A Department of Defense Dual-Use Technology Industrial Assessment.

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Table 17: Technology Profile for MEMS

Technology Characteristics	Principle of Operation	Dead Reckoning using acceleration and angular velocities
	Sensors	Gyroscopes, Accelerometers
	Observables	Specific force and angular velocity in each of the three direction components
	Navigation Information Provided	Position, velocity and attitude
	Other Characteristics	
Operational Environment	All environments including buildings, underground, and underwater	
System Error Sources	Gyro bias and scale factor, accelerometer bias and scale factor, sensor assembly errors, errors in initial conditions.	
System Error Characteristics	Height and horizontal errors are unbounded and grow rapidly.	
A Priori Information	Initial position, earth rotation rate and gravity field of the Earth	
Detectability	Not detectable	
Limitations	Current systems are far from providing m-level navigation accuracy	
Advantages	Low cost, lightweight, low power consumption, high data rate, Not detectable, passive, self-contained, global, autonomous	
Vendors	Allied Signal, Analog Devices (Norwood, MA, USA), Interstate Electronics Corporation (IEC), GNC Cooperation, Crossbow's Kearfott, Rockwell Collins	
Example Systems	MEMS/GPS IMU by IEC (member of L3 communication group), coremicro™ IMU AGNC™-2000 CMIMU, Crossbow's DMU-H6X μSCIRAS	
Accuracy Performance (Stand-alone mode)	Same as most tactical grade IMUs (1-10 deg/hr). MEMS-based IMUs usually used as bridging systems	

2.12 Nav Aid

A sensor/tool that supplies only partial information on the navigation states or that is used as a constraint on some of the navigation states will be called a navaid. Navaids can be classified into the following categories:

- Map-Aided Navigation (MAN): Algorithms that use maps to aid navigation are generally referred to as Map-Aided Navigation. They include a positioning sensor and a map-matching algorithm to update and bridge the position sensor results. Therefore, MAN can be considered as constraint on the position and azimuth of the navigation states vector.

- Navaid sensors: Sensors that provide partial information on the navigation state. They include, but are not limited to, velocity, attitude, and distance measuring sensors. They are extensively used in the automotive industry in stand-alone mode (e.g. odometer) or as part of an integrated system.

2.12.1 Pedometer

This very simple device counts the steps a user makes as they walk. A pedometer usually integrates using tri-axial accelerometers. A spring-balanced weight makes contact with a pin as the user takes a step. When the pedometer makes contact with the spring, which is usually connected to +5 volts (See Figure 1), the voltage at the microcontroller will fluctuate due to the bouncing inherent with mechanical switches. This connection completes an electrical circuit that signals the navigational unit indicating a step has taken place. A pedometer is not only accurate in counting the steps a person takes while walking but is also quite inexpensive, its cost ranging from $10 to $100.

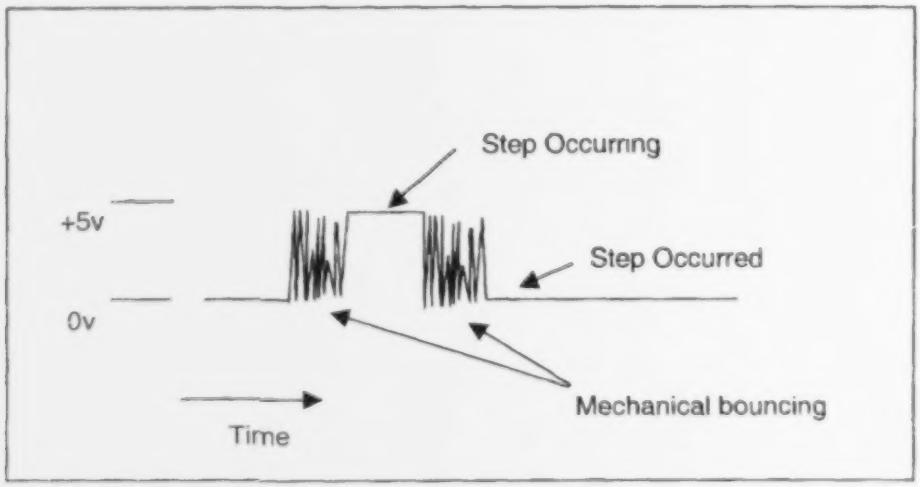

Figure 1: Electrical Representation of a Pedometer Step

Since pedometers are inexpensive, lightweight, and readily available, their use will increase as part of integrated systems. These sensors cannot be used without GPS. Because of variations in the length of a stride, they can be in error by 10-20 % of the travelled distance especially in mountainous areas. Because of the use of DGPS, calibration of the user's stride length can be done without "physically" measuring it. For example, if the user walks 10 meters as recorded by the Strider system, and the pedometer records 20 steps taken, the stride length would be 0.5 meters/step-taken. Then whenever the GPS signal is blocked, 0.5 meters will be associated with each step the user takes. In addition, whenever DGPS accuracy is obtained re-calibration of the stride length may occur. For information about the applications of pedometers in personal navigation systems, see Judd (1997).

Reference:

Judd, T. (1997), *A Personal Dead Reckoning Module*, Proceedings of ION GPS'97, Kansas City.

Table 18: Technology Profile for Pedometry

Technology Characteristics	Principle of Operation	Dead reckoning using distance measurements
	Sensors	Accelerometers
	Observables	Travelled distance as a function of the number of user strides and stride length
	Navigation Information Provided	Travelled distance and derived speed
	Other Characteristics	
Operational Environment	All environments on the surface of the earth, including buildings, city centres, heavily forested areas, mountainous areas (valleys) and underground	
System Error Sources	Change in stride length on steep or rough terrain	
System Error Characteristics	Relative and distance dependent	
A Priori Information	Estimating the length of the user stride (scale factor)	
Detectability	Not detectable	
Technology Limitations	Very low accuracy for navigation purposes.	
Technology Advantages	Not detectable, passive, self-contained, autonomous, global	
Vendors	Tandy Inc., Ultrack Inc.	
Example Systems	MICRONTA LCD Pedometer by Tandy Inc. and ULTRAK series by Ultrak Inc.	
Advantages	Very small size, low cost, lightweight	
Limitations	Generally used by joggers	
Accuracy Performance (Stand-alone mode)	2%-10% of the travelled distance	

2.12.2 Laser Range Finder

Table 19: Technology Profile for Laser Range Finding

Technology Characteristics	Principle of Operation	Laser: Light Amplification by Stimulated Emission of Radiation
	Sensors	Infrared semiconductor laser diode
	Observables	Distance/range to targets, range rates
	Navigation Information Provided	Position (if distance to three known positions is measured) and derived velocity
	Other Characteristics	To be used in positioning: Resection from three known positions (beacons) using ranges
Operational Environment	All environment on the surface of the earth, including buildings, city centres, heavily forested areas, mountainous areas (valleys) and underground	
System Error Sources	Divergence of the laser beam and pin pointing of targets	
System Error Characteristics	1. Distance dependent 2. Size of target (targets less than the laser beam at certain distance will not be detected)	
A Priori Information	Position of control points and/or map features (if not integrated with navigation sensors)	
Detectability	Detectible	
Limitations	1. Active and non-autonomous 2. Requires reflectors for long distances (> 600 m) 3. Not commonly used for Navigation 4. Usually integrated with GPS and Gyros if used for tracking	
Advantages	Self-contained, global, very small size, low cost, lightweight	
Vendors	Leica, Power Spectra	
Example Systems	Leica: MRF2000 Monocular Rangefinder Power Spectra : E-OR 230	
Accuracy Performance (Stand-alone mode)	0.1 m @ 50 m distance & 1-5 m @3000 m distance	

2.12.3. Magnetic Compasses

Compasses have been used for decades, providing an absolute heading for marine and airborne applications. All magnetic sensors determine the azimuth by sensing the components of the Earth's magnetic field through its three magnetic sensors. However, local disturbances in the Earth's magnetic field caused by nearby permanent magnets, electric currents, or large iron bodies can dramatically affect the derived azimuth. As a consequence of this phenomenon, the determined azimuth bias changes more in relation to location than with the time elapsed since the last update. Because the earth's magnetic field is the reference, the azimuth angles from magnetic compasses must be corrected for magnetic declination if they are to refer to true north. Fortunately, there are freely available global models of the Earth's magnetic field. These models provide all three components of the Earth's magnetic field for certain date, longitude, latitude and elevation. These models compute the estimated values of the Earth's magnetic field, including magnetic declination, based on the current International Geomagnetic Reference Field (IGRF) (NIMA, 2000). While results are typically accurate to 30 minutes of arc, solar storms can cause intense short-term disturbances in the magnetic field.

The accuracy of derived azimuths from magnetic compasses depends heavily on the degree to which the local magnetic field is being disturbed. Disturbances in the magnetic field can be divided into two categories: hard-iron and soft-iron. Hard-iron effects, or local fields, can be modelled as static fields such as those created by permanent magnets. Hard-iron distortions are significant in most systems. Soft-iron effects are created by the amplification of magnetic fields by highly permeable materials, such as ferrous metals. Most magnetic compasses implement several internal calibration routines that perform both hard-iron and soft-iron calibrations. For a review of hard-iron and soft-iron disturbances, see Caruso (2000) and for more details about calibration of magnetic sensors, see Gebre-Egziabher et al. (2001).

References:

Caruso, M.J. (2000), *Applications of Magnetic Sensors for Low Cost Compass Systems*, In Proceedings of IEEE Positioning, Location, and Navigation Symposium 2000, San Diego, CA, March 13-16, pp. 177-184.

Gebre-Egziabher, Demoz, Gabriel H. Elkaim, J. David Powell, Bradford W. Parkinson (2001), *A Non-Linear Two-Step Estimation Algorithm for Calibrating Solid-State Strapdown Magnetometers*, Presented at The International Conference on Integrated Navigation Systems in St. Petersburg Russia, May 2001. http://waas.stanford.edu/~wwu/gebre/.

National Imagery Mapping Agency (NIMA) (2000), *World Magnetic Model-2000*, Website. URL: http://www.ngdc.noaa.gov/seg/potfld/DoDWMM.shtml.

Table 20: Technology Profile for Magnetic Compasses

Technology Characteristics	Principle of Operation	Azimuth determination by sensing the components of the Earth's magnetic field
	Sensors	Magnetometers
	Observables	Components of the Earth's magnetic field
	Navigation Information Provided	Azimuth
	Other Characteristics	
Operational Environment	All environments on the surface of the earth, including buildings, city centres, heavily forested areas, mountainous areas (valleys) and underground	
System Error Sources	Very sensitive to local and global magnetic field disturbances such as bridges, railway tracks, and overpasses.	
System Error Characteristics	Determined azimuth bias changes more in relation to location than with the time elapsed since the last update	
A Priori Information	Approximate location (for estimating the magnetic declination)	
Detectability	Non-detectible	
Limitations		
Advantages	Self-contained, global, very small size, low cost, lightweight	
Vendors	Leica, Honeywell, KVH	
Example Systems	Leica: Digital Magnetic Compass DMC unit), Honeywell HMR3000 Digital Compass Module	
Accuracy Performance (Stand-alone mode)	Heading Accuracy*: $< 1^\circ$ for tilt $< 40^\circ$ $< 3^\circ$ $40^\circ <$ tilt $< 60^\circ$	

* Heading accuracy assumes the Earth's magnetic field is only disturbed by hard iron fields, and has been compensated through calibration.

2.12.4 Map Matching and Map-Aided Navigation (MAN)

To date, maps are considered one of the most common aids to navigation. They can be used as a sole means of navigation with users determining their location by feature matching. In this case, the relative locations of a set of visible features (including the more obvious features such as street signs) are matched to those indicated on the map. Maps are also used to put the positions generated by positioning systems into context. Positioning systems that locate and track land vehicles commonly overlay the observed position onto a digitized map (Hurst 1989); the positions are not necessarily translated to lie on the road. This is not the only way in which maps can be used in positioning systems. The features of the road network can be used to augment the actual positioning process. The collection of algorithms that do this are broadly grouped under the umbrella of map matching. However, a distinction will be made between systems that use the map to correct systematic sensor errors, termed map matching, and systems that use the map as an integral component of the position calculation, termed map-aided positioning.

Map matching is most commonly used as the means by which dead-reckoned navigation systems receive regular absolute position updates to correct for accumulated errors. In augmenting dead-reckoning systems, map matching reduces the drift errors and offers a source of absolute position information. Map-aided positioning refers to systems that use the street map vectors as a line-of-position to complement the position generated by other means such as the time-difference-of-arrival of a pair of radio signals. It is worth noting that neither of these techniques is sufficient within themselves; both must be integrated with a primary source of absolute or relative position measurement. The accuracy of map-matched systems is comparable to that of the underlying maps, approximately 15m. This, however, effectively represents a one-dimensional accuracy as the road is modeled by a straight line and it does not consider the situation where the vehicle is not on the road network. It also does not consider the problem of the system getting lost. Once the vehicle is lost there is no meaningful accuracy specification. Along similar lines, there is no meaningful specification for quantifying the likelihood that the map matching system will become lost. For a given city, the average distance driven between resets has some merit but it is not a good basis for comparing systems in different cities or even countries. It also means that the performance of systems can only be established once they are in frequent use. The underlying problem is that the likelihood of a map matching error is a function of many variables including the map accuracy, in terms of completeness and relative and absolute coordinate accuracy; the topology of the street network, some cities have a more convoluted network forcing more identifiable turns per unit of distance travelled, and the actual route taken, drivers frequently using freeways are more likely to experience errors.

The existence of map databases is one of the key requirements for MAN in land vehicle navigation because a digital road map is used to automate this process. Digital road maps are the basis for many functions besides navigation. Other applications of digital map databases includes pre-mission route planning and route calculation, en route guidance, and address matching. Geometric consistency and topological integrity are also essential in any digital road map used for navigation. There are several mapping companies and organizations that produce and maintain digital road maps. Current digital road maps support most of these map-related functions. For more detailed information about currently available digital road maps available worldwide, see Krakiwsky (1996).

References:

Hurst, G. C. (1989), *QUIKTRAK: A Unique AVL System*, Vehicle Navigation Information Systems Conference (VNIS '89), A60-A62.

Krakiwsky, E. J., (1996), *Assessment of Positioning and Navigation Technologies for Intelligent Transportation Systems*, A report prepared for TRANSPORT CANADA and INDUSTRY CANADA, Aerospace and Defence Branch, by Intelligent Databases International Ltd., Calgary, Canada.

2.13 Imaging

Imaging based systems have been used for more than two decades in robotics navigation applications in indoor environments, see Thompson and Pick (1993). Methods of vision-based navigation determine the current camera position and attitude by resection from at least three known points. The known points can either be control points or map features. The observables in this case are the image coordinates of these known points. By combining the coordinates of known points with their corresponding image coordinates in a photogrammetric bundle adjustment, the position and attitude of the camera can be determined. After estimating the initial position and attitude of the cameras, the system, in principle, can navigate by modeling the surrounding environment using photogrammetric techniques. Imaging-based systems, therefore, could be operated in all environments including buildings, under ground and underwater. Most recent work in Vision Based Systems (VBS), mainly autonomous robot navigation, has been done in structured indoor environments. Such environments are very easy to model since all the objects are static. A sampling of this work can be found in Judd, (1997), Tsubouchi and Yuta (1987). Error sources are mainly related to the sensor errors (interior geometry) and the accuracy with which the image coordinate of the known points can be identified and measured. The limitations to implementing VBS in indoor/outdoor environments are due the difficulties in developing smart algorithms that model such complex environments. Therefore, its not expected that VBS can be implemented as stand-lone navigation system but rather as a component of an integrated system. Therefore, imaging-based systems are seen more as a navigation aid in bridging navigation in environments not favourable to GPS (frequent signal blockage) and INS (when not able to perform ZUPTs).

References:

Thompson, W.B, and H.L. Pick, Jr. (1993), *Vision-Based Navigation*, Proceedings of the ARPA Image Understanding Workshop, April.

Tsubouchi, T. and S. Yuta (1987), *Map Assisted Vision System of Mobile Robots for Reckoning in a Building Environment*, Proceedings of the IEEE International Conference on Robotics and Automation, May, pp. 1978–1984.

Table 21: Technology Profile for Imaging-based Systems

Technology Characteristics	Principle of Operation	Resection from known points (control points or map features)
	Sensors	Digital cameras
	Observables	Image pixels.
	Navigation Information Provided	Position and attitude
	Other Characteristics	
Operational Environment	All environments including buildings, underground, and underwater	
System Error Sources	Sensor calibration errors; Feature measuring errors	
System Error Characteristics	Distance dependent	
A Priori Information	1. The coordinates of at least three points for initial position and attitude 2. Parameters defining internal geometry of the camera (focal length and principal point coordinates)	
Detectability	Not detectable (receiver of natural radiation)	
Limitations	The need for ground control points, image matching, target visibility.	
Advantages	Non-autonomous, local	
Vendors	Conceptual, no actual implementation as a stand-alone system	
Example Systems	Stereo-vision systems for robotics applications	
Accuracy Performance (Stand-alone mode)	1-2 m for stereo-bases system with base 0.2-0.3 m	

2.14 Integrated Systems

It is, of course, possible to integrate a number of different technologies into one system. The advantage of such an approach is that complementary technologies will offset each other's weaknesses. The Defense Advanced Research Project Agency (DARPA) has developed an integrated geolocation system, named the Small Unit Operations/Situation Awareness System (SUO/SAS), for use by soldiers in multiple environments (Jacobson et al., 2001). SUO/SAS integrates GPS data, TOA measurements, IMU measurements, barometric altimeter data, and digital magnetic compass data in a single navigation Kalman filter. The system uses GPS in outdoor environments only. The TOA measurements made by the mobile equipment are actually two-way ranges between pairs of mobiles. As a result, in the absence of GPS, only relative positioning between mobiles is achieved. For ground-based TOA systems, vertical geometry is typically poor. Therefore, a barometric altimeter is used to significantly enhance the accuracy of the vertical dimension when GPS is unavailable. The indoor accuracy goals for SUO/SAS were 9 m (95%) in the horizontal and 2 m (95%) in the vertical. As tested, the system delivered an indoor horizontal accuracy ranging from 8.9 m to 18 m (95%). For the next phase of SUO/SAS, improved TOA transceivers are being developed. These new transceivers will include a

multipath mitigation technique called Quadrature Multiple Frequency Ranging. With these new transceivers, the horizontal accuracy goal for SUO/SAS will be 1 m (95%). Note that no effort was made to minimize the mobile equipment.

Reference:

Jacobson, E., T. Lee, C. Popeck, M. Martorana, S. Sokolowski, (2001), *SUO/SAS Geolocation: Land Navigation Using Multiple Integrated Sensors*, Proceedings of ION 57th Annual Meeting/CIGTF 20th Biennial Guidance Test Symposium, Albuquerque NM, June 11-13, pp. 622-633.

Table 22: Technology Profile for a Multisensor Integrated System

Technology Characteristics	Principle of Operation	Kalman navigation filter using various sensors.
	Sensors	GPS, TOA transceivers, IMU, Barometer, Magnetic Compass
	Observables	GPS pseudoranges (and carrier phase?) ranges between mobile transceivers acceleration and angular velocity atmospheric pressure heading
	Navigation Information Provided	3D position fix
	Other Characteristics	o Rockwell Collins GPS/INS Navigator o IMU is Honeywell HG1700 Ring Laser Gyro o TOA transceivers use DS spread spectrum with chip rate of 32 Mcps o Two way ranging permits use of unsynchronized clocks o Leading edge measurement of correlation peak o TOA ranging provides relative position of transceivers. Made absolute with GPS. o TOA ranging rate of 1Hz o Honeywell PPT-R pressure transducer yields independent altitude estimate. o Precision Navigation TCM2 Digital Magnetic Compass provides initial heading.
Operational Environment	Indoor and outdoor.	
System Error Sources	Multipath on TOA ranges	
System Error Characteristics	Large vertical position error for TOA-only mode due to poor vertical geometry of TOA transceivers. Remedied by use of barometer.	

<table>
<tr><td>A Priori Information</td><td></td></tr>
<tr><td>Detectability</td><td>TOA signal "invisibility" and resistance to jamming inherent in spread spectrum communications.</td></tr>
<tr><td>Limitations</td><td>- Phase 2 TOA transceivers had short range (200 m to 350 m) due to 915 MHz carrier frequency. A carrier frequency of 250 MHZ would be better.
- Phase 2 TOA transceivers did not utilize Quadrature Multiple Frequency Ranging multipath mitigation as will Phase 3 TOA transceivers.</td></tr>
<tr><td>Advantages</td><td>- May utilize GPS outdoors
- IMU smooths errors in TOA measurements and allows system operation during brief outages of TOA.
- Reference or fixed transceivers not strictly necessary for TOA measurements (if GPS provides absolute reference)</td></tr>
<tr><td>Vendors</td><td></td></tr>
<tr><td>Example Systems</td><td>SUO/SAS (Small Unit Operations/Situation Awareness System) developed by DARPA.</td></tr>
<tr><td>Accuracy Performance (Stand-alone mode)</td><td>
<table>
<tr><td>Horizontal(95%)</td><td>Open-Outdoor</td><td>Suburban</td><td>Indoor</td></tr>
<tr><td>W/GPS</td><td>4.4 m</td><td>7.4 m</td><td>N/A</td></tr>
<tr><td>WO/GPS</td><td>1.9 m</td><td>6.4 m</td><td>8.9 – 18 m</td></tr>
</table>
</td></tr>
</table>

3. ANTICIPATED PERFORMANCE OF POTENTIAL SYSTEMS

The following section gives the performances for a number of selected systems based on the technologies (or a combination of technologies) described in the previous section. The performance characteristics are given for an outdoor capability in addition to four indoor environments, namely Case1 to Case 4 as follows:

Case 1: Three-story wooden building of construction consistent with a large private residence

Case 2: Twenty-story steel and glass building of construction consistent with an urban office tower.

Case 3: Underground earthen, concrete and steel structure of construction consistent with a subway tunnel.

Case 4: Large reinforced concrete building of construction consistent with a military headquarters.

3.1 Ground-Based Spread Spectrum

Table 23: Anticipated Performance of Ground-Based Spread Spectrum Technology

Characteristic	Outdoor Capability[1]	Anticipated Indoor Capability Case 1	Anticipated Indoor Capability Case 2	Anticipated Indoor Capability Case 3	Anticipated Indoor Capability Case 4
Performance					
Accuracy, Horizontal (m)	0.3	2	3	<5	<5
Accuracy, Vertical [3] (m)	0.6	3-4	3-4	4-5	4-5
Velocity	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement
Update Rate (Hz)	1	1	1	1	1
Operating Time	†	†	†	†	†
Set-up / Calibration Time (min)	††	††	††	††	††
Emission Control	active [2]	active [2]	active [2]	active [2]	active [2]
Physical					
Weight (kg)	2	2	2	2	2
Volume (cm^3)	750	750	750	750	750
Cost	unknown	unknown	unknown	unknown	unknown

1 Assumes line-of-sight between transmitters and receivers

2 Active in the sense that the mobile will either transmit RF location signals or observations that are observed at the mobile

3 Vertical accuracy assumes good VDOP (i e pseudolite installed above the receiver)

† Operating time of the system will be determined by the mobile transmitter battery life This is unknown at this time

†† System set-up time will depend on the time to install the beacons and accurately determine their positions

3.2 Ground-Based Spread Spectrum (GBSS)+ Self-Contained Sensors

Table 24: Anticipated Performance of Ground-Based Spread Spectrum + Self-Contained Sensors Technology

Characteristic	Outdoor Capability[1]	Anticipated Indoor Capability Case 1	Anticipated Indoor Capability Case 2	Anticipated Indoor Capability Case 3	Anticipated Indoor Capability Case 4
Performance					
Accuracy, Horizontal (m)	0.3 [2]	< 2 [3]	< 2 [3]	< 2 [3]	< 2 [3]
Accuracy, Vertical (m) [6]	0.6 [2]	< 1 [3]	<1 [3]	<1 [3]	<1 [3]
Velocity	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement
Update Rate	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement
Operating Time	†	†	†	†	†
Set-up / Calibration Time (min)	†† / 5 [4]	†† / 5 [4]	†† / 5 [4]	†† / 5 [4]	†† / 5 [4]
Emission Control	active [5]	active [5]	active [5]	active [5]	active [5]
Physical					
Weight (kg)	4	4	4	4	4
Volume (cm^3)	≈ 3500	≈ 3500	≈ 3500	≈ 3500	≈ 3500
Cost	GBSS + $15K	GBSS + $15K	GBSS + $15K	GBSS + $15K	GBSS + $15K

1 Assumes line-of-sight between transmitters and receivers
2 Self-Contained Sensors are not needed
3 With ZUPT every 3-4 minutes and Baro Altimeter Aiding.
4 For gyro-compassing and fine alignment of the Self-Contained Sensors
5 Active in the sense that the mobile will either transmit RF location signals or observations that are observed at the mobile
6 Vertical accuracy assumes good VDOP (i.e. pseudolite installed above the receiver)
† Operating time of the system will be determined by the battery life.
†† System set-up time will depend on the time to install the beacons and accurately determine their positions.

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3.3 Ultra Wideband

Table 25: Anticipated Performance of Ultra Wideband Technology

Characteristic	Outdoor Capability[1]	Anticipated Indoor Capability Case 1	Anticipated Indoor Capability Case 2	Anticipated Indoor Capability Case 3	Anticipated Indoor Capability Case 4
Performance					
Accuracy, Horizontal (m)	0.3 [2]	0.3 [2]	1.8 [2]	1.0 [2]	4.0 [2]
Accuracy, Vertical (m)	0.15 × VDOP [3]	0.15 × VDOP [3]	0.9 × VDOP [3]	0.5 × VDOP [3]	2.0 × VDOP [3]
Velocity	At least 2 m/s [4]	At least 2 m/s [4]	At least 2 m/s [4]	At least 2 m/s [4]	At least 2 m/s [4]
Update Rate	Meets desirable requirement [5]	Meets desirable requirement [5]	Meets desirable requirement [5]	Meets desirable requirement [5]	Meets desirable requirement [5]
Operating Time	†	†	†	†	†
Set-up / Calibration Time (min)	††	††	††	††	††
Emission Control	active [6]	active [6]	active [6]	active [6]	active [6]
Physical					
Weight (kg)	≈ 2 - 3	≈ 2 - 3	≈ 2 - 3	≈ 2 - 3	≈ 2 - 3
Volume (cm^3)	≈ 1300	≈ 1300	≈ 1300	≈ 1300	≈ 1300
Cost	unknown	unknown	unknown	unknown	unknown

1 Assumes line-of-sight between transmitters and receivers

2 Horizontal Accuracy = Range Error × HDOP An HDOP of 2 has been assumed

3 Vertical Accuracy = Range Error × VDOP Although speculating on VDOP is difficult, it is safe to assume that VDOP will be significantly larger than HDOP Therefore, vertical accuracy will be significantly poorer than horizontal accuracy.

4 The UWB positioning system developed by Multispectral Solutions Inc. has apparently been tested at walking speed (about 2 m/s) The system should continue to operate and maintain accuracy at higher velocities

5 Some systems claim an update rate of 100 Hz.

6 Active in the sense that the mobile may transmit both RF location signals and observations that are observed at the mobile.

† Operating time of the system will be determined by the mobile transmitter battery life. This is unknown at this time.

†† System set-up time will depend on the time to install the beacons and accurately determine their positions Installation time will most likely be short (perhaps only a few seconds per beacon). Position determination of the beacons could take longer depending on the method used to determine their position Indoors, blueprints of the building could be used If indoor locations for the beacons are chosen in advance, set-up time will consist largely of beacon installation If beacons are deployed outdoors, methods such as DGPS could be used to determine their position. Given GPS receivers with L1/L2 and carrier phase capability, plus adequate RTK software, DGPS occupation times of a few minutes will result in beacon positions with accuracy of 1 cm or better Calibration may consist of determining the turn around delay within each beacon. This should be a constant, however, and as such, no calibration is necessary for each deployment of the system

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3.4 Ultra Wideband + Self-Contained Sensors

Table 26: Anticipated Performance of Ultra Wideband + Self-Contained Sensors Technology

Characteristic	Outdoor Capability[1]	Anticipated Indoor Capability Case 1	Anticipated Indoor Capability Case 2	Anticipated Indoor Capability Case 3	Anticipated Indoor Capability Case 4
Performance					
Accuracy, Horizontal (m)	0.3 [2,3]	0.3 [2,3]	< 2 [5]	1 [2,3]	< 2 [5]
Accuracy, Vertical	0.15 m × VDOP [3,4]	0.15 m × VDOP [3,4]	<1 m [5]	<1 m [5]	<1 m [5]
Velocity	At least 2 m/s [8]	At least 2 m/s [8]	At least 2 m/s [8]	At least 2 m/s [8]	At least 2 m/s [8]
Update Rate	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement	Meets desirable requirement
Operating Time	†	†	†	†	†
Set-up / Calibration Time	†† / 5 [6]	†† / 5 [6]	†† / 5 [6]	†† / 5 [6]	†† / 5 [6]
Emission Control	active [7]	active [7]	active [7]	active [7]	active [7]
Physical					
Weight (kg)	5	5	5	5	5
Volume (cm^3)	≈ 4500	≈ 4500	≈ 4500	≈ 4500	≈ 4500
Cost	UWB + $15K	UWB + $15K	UWB + $15K	UWB + $15K	UWB + $15K

1 Assumes line-of-sight between transmitters and receivers.

2 Horizontal Accuracy = Range Error × HDOP. An HDOP of 2 has been assumed

3 Self-Contained Sensors are not needed

4 Vertical Accuracy = Range Error × VDOP Although speculating on VDOP is difficult, it is safe to assume that VDOP will be significantly larger than HDOP Therefore, vertical accuracy will be significantly poorer than horizontal accuracy

5 With ZUPT every 3-4 minutes and Baro Altimeter Aiding

6 For gyro-compassing and fine alignment of the Self-Contained Sensors

7 Active in the sense that the mobile may transmit both RF location signals and observations that are observed at the mobile.

8 The UWB positioning system developed by Multispectral Solutions Inc has apparently been tested at walking speed (about 2 m/s) The system should continue to operate and maintain accuracy at higher velocities

† Operating time of the system will be determined by the mobile transmitter battery life. This is unknown at this time

†† System set-up time will depend on the time to install the beacons and accurately determine their positions. Installation time will, most likely be short (perhaps only a few seconds per beacon) Position determination of the beacons could take longer depending on the method used to determine their position. Indoors, blueprints of the building could be used. If indoor locations for the beacons are chosen in advance, set-up time will consist largely of beacon installation. If beacons are deployed outdoors, methods such as DGPS could be used to determine their position Given GPS receivers with L1/L2 and carrier phase capability, plus adequate RTK software, DGPS occupation times of a few minutes will result in beacon positions with accuracy of 1 cm or better Calibration may consist of determining the turn around delay within each beacon This should be a constant, however, and as such, no calibration is necessary for each deployment of the system

4. TECHNOLOGY COMPARISON

This section provides a cross-comparison between the various technology systems presented in the previous section. The performance characteristic for each system is compared against the requirements given in Section 1 and are denoted E for meeting essential requirements, D for meeting desirable requirements, N when it does not meet either requirement and U when the performance is not known (or not available in the open literature).

4.1 Case 1

Three-story wooden building of construction consistent with a large private residence

Table 27: Technology Comparison for Case 1

System	Ground-Based Spread Spectrum	Ground-Based Spread Spectrum + Self-Contained Sensors	Ultra Wideband	Ultra Wideband + Self-Contained Sensors
Performance				
Accuracy, Horizontal	N	N	E	D
Accuracy, Vertical	N	E	E	E
Velocity	D	D	D	D
Update Rate	E	D	D	D
Operating Time	E	E	E	E
Set-up / Calibration Time	N	N	N	N
Emission Control	E	E	E	E
Physical				
Weight	E	E	E	E
Volume	E	N	E	N
Cost	E	E	E	E

E = Meets essential requirements
D = Meets desirable requirements
N = Does not meet either requirement
U = Unknown (not available in open literature)

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4.2 Case 2

Twenty-story steel and glass building of construction consistent with an urban office tower.

Table 28: Technology Comparison for Case 2

System	Ground-Based Spread Spectrum	Ground-Based Spread Spectrum + Self-Contained Sensors	Ultra Wideband	Ultra Wideband + Self-Contained Sensors
Performance				
Accuracy, Horizontal	N	N	N	N
Accuracy, Vertical	N	E	N	D
Velocity	D	D	D	D
Update Rate	E	D	D	D
Operating Time	E	E	E	E
Set-up / Calibration Time	N	N	N	N
Emission Control	E	E	E	E
Physical				
Weight	E	E	E	E
Volume	E	N	E	N
Cost	E	E	E	E

E = Meets essential requirements
D = Meets desirable requirements
N = Does not meet either requirement
U = Unknown (not available in open literature)

4.3 Case 3

Underground earthen, concrete and steel structure of construction consistent with a subway tunnel.

Table 29: Technology Comparison for Case 3

System	Ground-Based Spread Spectrum	Ground-Based Spread Spectrum + Self-Contained Sensors	Ultra Wideband	Ultra Wideband + Self-Contained Sensors
Performance				
Accuracy, Horizontal	N	N	E	E
Accuracy, Vertical	N	E	E	D
Velocity	D	D	D	D
Update Rate	E	D	D	D
Operating Time	E	E	E	E
Set-up / Calibration Time	N	N	N	N
Emission Control	E	E	E	E
Physical				
Weight	E	E	E	E
Volume	E	N	E	N
Cost	E	E	E	E

E = Meets essential requirements
D = Meets desirable requirements
N = Does not meet either requirement
U = Unknown (not available in open literature)

4.4 Case 4

Large reinforced concrete building of construction consistent with a military headquarters.

Table 30: Technology Comparison for Case 4

System	Ground-Based Spread Spectrum	Ground-Based Spread Spectrum + Self-Contained Sensors	Ultra Wideband	Ultra Wideband + Self-Contained Sensors
Performance				
Accuracy, Horizontal	N	N	N	N
Accuracy, Vertical	N	E	N	D
Velocity	D	D	D	D
Update Rate	E	D	D	D
Operating Time	E	E	E	E
Set-up / Calibration Time	N	N	N	N
Emission Control	E	E	E	E
Physical				
Weight	E	E	E	E
Volume	E	N	E	N
Cost	E	E	E	E

E = Meets essential requirements
D = Meets desirable requirements
N = Does not meet either requirement
U = Unknown (not available in open literature)

5. PROPOSED TECHNOLOGY DEMONSTRATORS AND PLANS

Given the limitations of satellite-based RF navigation systems and the high drift rate of inertial navigation systems, an operational solution will likely combine ground-based RF and INS technologies, supplemented with a short-range differential barometry system for the height component. However, the propagation performance of RF signals through various building materials must first be quantified prior to conducting a full RF/INS test. Equipment must be available to conduct a RF signal propagation performance test. Two RF tests are proposed herein, one using ground-based spread spectrum at 1.5 GHz and another using ultra wideband technologies. Equipment and associated characteristics are well known in the case of the first system and a relatively detailed proposal in described in Section 5.1. Ultra wideband equipment is emerging for indoor location and performance evaluation should become possible by late 2002. The general procedure will likely be similar to that of ground-based spread spectrum testing. Only a brief description is, therefore, given in Section 5.2

No integrated ground RF/INS/differential barometry test system plan is proposed at this time as the INS equipment and procedures to be tested will depend on RF system performance test results.

5.1 Ground-based Spread Spectrum

Existing ground transmitters (pseudolites) and receivers developed for GPS can be used. Based on experience gathered at the University of Calgary during the past few years regarding the technical problems associated with the outdoor and indoor use of pseudolites (Morley and Lachapelle 1998a, b; O'Keefe et al., 1999), the following tasks are proposed:

1. Determine the feasibility of using CDMA-modulated GPS pseudolites operating at 1.5 GHz to analyse the penetration and accuracy performance of such signals through different types of buildings for accurate ranging purposes. This includes dealing with the following issues:
    - Outdoor GPS pseudolite signal transmission stability using a stable FTS (Frequency and Time Standard) source, e.g., integration with a GPS receiver operating in conjunction with the pseudolite.
    - Selection, integration and testing of a highly directional (narrow beam) transmission antenna (to concentrate power and avoid leakages outside the area of interest to avoid jamming neighbouring GPS receivers). A similar antenna will also be tested at the receiver.
    - Investigate and select pulse rate and period to avoid jamming caused by differential levels of absorption between two pseudolite paths coming from different directions, and ensure successful integrated measurement by GPS receiver.
    - Determine GPS CDMA PRN numbers to be used by pseudolites to ensure successful tracking by receivers. Have manufacturer (NovAtel Inc) modify receiver firmware as required to deal with this problem and with the built-in

navigation message problem that has been an issue in the past when tracking pseudolites.

2. Develop methods to deal with implementation issues such as: pseudolite and receiver time synchronization/frequency stability, the near/far transmission problem, signal multipath, antenna directivity, etc.
    - Develop a method to synchronize the indoor GPS receiver with GPS time by using a high accuracy Rubidium FTS to "transport" time from outdoors to indoors. An accuracy of a few ns is needed in order to preserve a high ranging resolution (1 ns is equivalent to 30 cm in range) and quantify the magnitude of multipath.
    - Deal with the problem of frequency stability at both pseudolites and receivers (the Doppler shifts of the transmitting pseudolites are not always known due to frequency instability – this can increase the signal search time at the receiver end). Also if two pseudolites have the same Doppler shift, one pseudolite will jam the other.

3. Assemble, integrate and test equipment for experimentation, including data collection. This may require seeking the support of a GPS equipment manufacturer to assist with receiver firmware modifications required to conduct experiments with the pseudolites.
    - Develop a method to synchronize an indoor GPS receiver with GPS time by using a high accuracy Rubidium FTS.
    - Interface with NovAtel Inc to have further GPS receiver firmware modifications if/as required.
    - Modify the rotating level arm developed by UofC (Ma 2000) to accept a receiver with an antenna that has a high omni-directional gain in the horizontal plane. Such a rotational motion will produce antenna diversity which will be advantageous to study multipath. With this assembly, the position of the antenna will be independently known with an accuracy of better than 1 cm. The length of the lever will be adapted to the size of the rooms in which the experiments occur.

4. Design and conduct outdoor-to-indoor transmission experiments in sufficiently different conditions to draw significant conclusions.
    - Select a few test sites where the pseudolites can be mounted in a higher location than the receiver inside the buildings to transmit with a significant negative elevation angle to avoid jamming of GPS receivers operating in the area. At least two or three different buildings with different material should be selected.
    - Inside each building, several occupation points (e.g. at least 5) with different characteristics with respect to the line-of-sight from the pseudolites should be selected and marked for repeated observations.
    - Select at least three sites for indoor kinematic testing with the rotating lever arm.

- Independently measure the direct slant range between each occupation point and the pseudolite antennas with an accuracy better than 2 dm using standard survey techniques.
- Prepare sketches of the occupation points, location of the pseudolite, and location and general characteristics of surrounding walls, ceilings, floors and windows. Complement with pictures to facilitate later evaluation of results.
- Conduct the observations in static mode at each occupation point and record all measurements. Each point is to be occupied in static mode for periods of 15 minutes for each scenario. Scenarios will be varied to study the impact of transmitted signal power, antenna effect (narrow beam versus high gain in the vertical plane/omni-directional in the horizontal plane).
- Sites selected for kinematic evaluation will be occupied for up to several hours. Different velocities will be tested to analyse the effect on C/N_o, multipath and Doppler shifts.

5. Evaluate the results of the experiments with particular emphasis on received signal characteristics such as signal strength, timing/ranging accuracy, Doppler shifts, multipath effects, etc. to determine their suitability for indoor location under the various conditions tested.
   - Analyse C/N_o as a function of time, transmitted signal power, receiver antenna, and location with respect to surrounding material.
   - Derive absolute ranges from time measurements. This will be possible if time synchronization between pseudolites and receivers is successful. If not, a bias that is expected to be constant can be estimated from the redundant observations and removed. Analyse range accuracy as a function of time, transmitted signal power, antenna, and location with respect to surrounding material. Deduce multipath from this analysis.
   - Examine correlation between multipath and C/N_o to determine how C/N_o could be used to qualitatively assess "thickness" of material and/or multipath encountered.
   - Analyse Doppler measurements as a function of multipath. This will only be possible if the pseudolite and receiver frequency can be stabilized successfully. Otherwise, the use of a double-difference method with two pseudolites and two receivers operating simultaneously might be possible, although such an experiment will likely be outside the scope of this phase.

6. Provide recommendations for the future potential of this technology for this application along with further prototype developments, if applicable. Depending on the results, recommend a more extensive set-up to assess accuracy performance in 3D.
   - Discuss frequency and time synchronization issues between transmitters and receivers.
   - Discuss signal transmission power versus multipath occurrence.

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- Discuss the possibility of using a different coding technique.
- Discuss ranging accuracy obtained and possible methods/approaches to improve accuracy.
- Formulate a subsequent experiment involving a minimum of three pseudolites and an accurate differential barometry and INS system to test location of a moving user inside a building, should the above conclusions warrant such an experiment.

Estimated Level of Effort:

Three to four months, $60,000, for an initial evaluation.

References:

Ma, C. (2000), *Construction of a Kinematic Platform for GPS Receiver and Antenna Testing*, Internal Report, Dept of Geomatics Engineering, University of Calgary.

Morley, T., and G Lachapelle (1998a), *Pseudolite Augmentation for OTF Ambiguity Resolution in Shipborne Mode*, Journal of Surveying Engineering, American Society of Civil Engineers, 124, 1, 26-39.

Morley, T., and G. Lachapelle (1998b), *GPS Augmentation with Pseudolites for Navigation in Constricted Waterways*, Navigation, The Institute of Navigation, Alexandria, VA, 44, 3, 359-372.

O'Keefe, K., J. Sharma, M.E. Cannon, and G. Lachapelle (1999), *Pseudolite-Based Inverted GPS Concept for Local Area Positioning*, Proceedings of GPS99 (Session D4, Nashville, 14-17 September), The Institute of Navigation, Alexandria, VA , 1523-1529.

5.2 Ultra Wideband

Positioning systems that employ ultra wideband signals demonstrate excellent potential for positioning personnel indoors. The small amount of published test data that exists suggests that, depending on geometry, the accuracy of such systems will be in the 1 – 2 m range for many indoor environments. It also appears that ultra wideband positioning technology will meet most, if not all of the other requirements for TIPS (i.e. size, weight, etc.). Unfortunately, the published data is very limited and is generally generated by companies who are developing proprietary systems. Currently, ultra wideband positioning hardware is not available for testing purposes. Multispectral Solutions Inc., Aether Wire and Location Inc., and Time Domain were all contacted regarding the availability of systems to purchase. All three vendors responded that systems were not available for purchase. As a result, it appears that independent, third party testing of ultra wideband positioning systems has not yet been performed.

It is proposed that the availability of ultra wideband positioning hardware be monitored. When such hardware becomes available, a system of extent large enough for testing in all relevant environments should be purchased and tested. In particular, UWB positioning performance should be compared with that of spread spectrum positioning to determine if UWB technology holds any advantage in multipath mitigation.

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This study identifies technologies that can be considered in a future R&D project to implement a proof-of-concept technology demonstration that will attempt to achieve 1 metre 3D indoor positioning accuracy under the widest possible range of operating environments. Existing and emerging RF and self-contained technologies are reviewed for indoor location and to propose potential systems that could be considered for evaluation.

14 KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document They should be selected so that no security classification is required Identifiers such as equipment model designation, trade name, military project code name, geographic location may also be included If possible keywords should be sele from a published thesaurus e g Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible t select indexing terms which are Unclassified, the classification of each should be indicated as with the title)

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